TEST APPROACH

- o CONDUCT A SERIES OF TESTS ON SCALED MODELS OF OFF-SHORE TYPICAL STRUCTURES
  - 4 LEG PLATFORM
  - K JOINT
- o TEST IN A MEANINGFUL WAY REPRESENTATIVE OF OFF-SHORE PLATFORMS
- o TESTS TO BE CONDUCTED IN A BLIND MODE
- o <u>FAILURE MECHANISMS</u> PROPOSED:
  - SEVERED MEMBERS
  - JOINT CRACKING
- o NON-FAILURE CHANGES PROPOSED:
  - CHANGE IN DECK MASS
  - CHANGE IN BASE SUPPORT

FIGURE 2

combination of two techniques may have been very powerful and more effective. On the other hand, one technique may be better than the others for a particular application or even for this particular test series.

As Figure 2 shows, we decided to run first vibration tests on a scaled model of a 4 leg offshore drilling platform. The platform model was fabricated at the University of Maryland's Physics Department under the direction of Dr. Jackson Yang and was used for the entire series of tests.

In the program, the different NDE method advocates' tests were run "piggyback" on the same test structure. Some advocates had previous experience with this type of test structure (prior to the present tests); others did not. The tests conducted appear to be meaningful in terms of the advocates' ability to detect or not to detect damage.

The tests were all conducted in a blind mode. Advocates or the investigators operated in a hands-off environment. They were not permitted to see the platform while it was being tested. The test failure mechanisms were selected by the evaluator from a set of pre-published failure mechanisms that the candidates or advocates had been given before the tests.

Although they had a list of failures that could possibly occur, they did not know which ones would be selected for the test programs.

As part of the program, we made a search of independent test laboratories to run these tests. We looked through the Department of Defense, NASA, and commercial firms. Some agencies had no time in the proper time slot. Others' budgets were too high. We found one agency that was both cooperative, and extremely interested in the program.

That facility was located at the NASA Goddard Space Flight Center in Greenbelt, Maryland, where all of these tests were subsequently conducted.

Figure 3 is an overview of the Program's participants. We have the two sponsoring organizations. We, as Mega Engineering, were the independent test coordinators.

Next, the NASA Goddard Space Flight Center is shown as the Agency which performed tests, and under that organization is the Northrup Corporation, which worked on a contract basis with NASA Goddard Space Flight Center to carry out the tests.

PROGRAM GOALS:

PRIMARY GOALS:

TO EVALUATE TECHNIQUES WHICH MERIT FURTHER DEVELOPMENT

SECONDARY GOALS:

(A) DISCRIMINATE BETWEEN FAILURE AND NON-FAILURE

(B) DISCRIMINATION OF THE DEGREE OF DAMAGE

(C) DISCRIMINATION OF LOCATION OF DAMAGE

FIGURE 1

The Round Robin Test Program
by Dr. Richard E. Dame,

Mega Analytical Research Services,
Silver Spring, Maryland.

This report presents to you the results of the Round Robin series of nondestructive tests which were conducted on a scale model platform.

This project was intended to evaluate techniques which had been sponsored and funded by both the ONR and the DOI/MMS. Our function in the program was to act as an independent coordinator and test evaluator.

Up to the date we became involved, there had been a number of advocates of different NDE testing techniques, and among these testing techniques, some had been sponsored and funded for Research by the ONR and MMS: others had not.

Dr. Nicholas Perrone of the ONR proposed the idea that a good test of the techniques would be one conducted in a "blind mode." He wanted an objective testing agency, a qualified testing laboratory, and an objective reviewer who could determine whether damage could be detected in a blind mode by these different NDE methods and, if so, what kinds of damage could be detected.

Figure 1 shows that the Round Robin program had several objectives. The primary objective was to find out whether the techniques previously sponsored to date should receive further funding, whether they indeed were effective in locating incipient cracks, major damage, or failure.

A secondary goal for the program was to evaluate each NDE method's ability to discriminate between failure and nonfailure. To define this damage, we determined which of the NDE methods could detect various damage levels, whether it was moderate, or severe, damage, or whether there was no damage in a test. Then we evaluated each method's ability to discriminate the location of that failure in the structure.

After we proceeded through this test series, we discovered one unfortunate thing. The NDE methods under our testing techniques were compared against each other. However, each may have its own particular niche in the NDE field. Pitting one against another in a competitive overall test to determine which one is better for a limited set of test constraints is probably not a very good idea. Perhaps some

Dr. Nickolas Basdekas, Office of Naval Research:

Before I say anything representing the Office of Naval Research (ONR), I should give credit to my previous supervisor, Dr. Nick Perrone of ONR, and to Mr. John Gregory, from the Materials Management Service, who is not here. Jointly, they are responsible for our research in the nondestructive evaluation of structures.

I have inherited the task that Dr. Perrone was responsible for initiating, and we are going to hear today the accomplishments that investigators through the years have reported.

The ONR's interest is primarily basic in its aspects, and certainly solving a basic problem is of value only when you find some application at the end of it. That is the primary interest of not only ONR, but also of the MMS and this is the best kind of marriage that can take place.

So we are going to share our accomplishments among the research community and the technology-oriented individuals that came here. I would like, through the principal investigators or those who represent them, to find out some of the following:

What are the new Non Destructive Evaluation (NDE) ideas? What did we get out of the old ones? What did we not get that was expected? And where do we go from here, to make the nondestructive evaluation of structures?

Most probably NDE methods started from the qualitative R&D to the -- strictly speaking -- quantitative research. That is, it is nice to diagnose that something is wrong, but how to make the exact diagnosis of what is wrong is the necessary intermediate link to propose the proper cure.

So with that introduction, I will finish by asking for your recommendations for my own benefit, so that I can decide what ONR is going to support in that direction.

TRANSCRIPTS OF THE OFFICE OF NAVAL RESEARCH AND MINERALS MANAGEMENT SERVICE WORKSHOP ON NONDESTRUCTIVE TESTING METHODS

Introduction by Mr. Charles Smith, DOI, MMS.

MR. SMITH: This is a joint effort between the Minerals Management Service and the Office of Naval Research to evaluate several of the NDE monitoring techniques for offshore platforms and other structures.

As some of you may know, the (MMS) grew out of the Conservation Division of the U.S. Geological Survey. The Secretary of the Interior (James Watt) created the MMS in order to centralize the Outer Continental Shelf (OCS) operations into one Government agency.

The Research and Development Program evolved in the organization as a Technology Assessment and Research Program, which is contained in the Technology Assessment Research Branch of the Offshore Inspection and Enforcement Division.

Our program has three main purposes:

(1) First, to conduct technology assessment, to determine the current State-of-the-Art and practice, and to identify technology gaps that might appear fruitful for further study.

(2) Second, it quantifies the applicability of technologies to the MMS operational needs where deemed necessary and which is not otherwise available.

(3) Third, to promote joint industry-government projects on new technologies required to have safe and pollution-free operations in new, harsh frontier environments.

Copies of our previous technical report are available. It contains in detail some of our projects as well as additional information on the scope of our program. We are presently updating this document.

Again, this is a workshop, and I encourage each of you all to participate in the discussions, and if I may assist you in any way during your visit with us, please let me know.

verified for more field structures. There is apparently still concern over the separation of acoustic emissions traceable to actual crack growth compared to those which are sounds from simply crack rubbing. There still appears to be a need for support for theoretical work and laboratory work in these areas.

As each of the various NDE techniques develop there is a strong requirement to involve cooperation between research and industry. Defining the importance of any structural changes discovered to actual structural integrity platforms must be absolutely determined. The exact levels of damage or type of defects which are important to detect early must be identified.

The non-destructive evaluation techniques currently being developed by industry and institutions cover a very broad range considering the changes that can be observed. These range from gross amounts of structural damage to early stages of metallic cracking. Industry representatives and researchers need to work more closely together than they have in the past to decide exactly what damage is important to minimize wasting resourses and to obtain the maximum effort for limited funds.

For instance, a few of the techniques discussed at the Workshop are aimed at detecting or monitoring crack growth in a local area. It has been suggested that these methods be applied to a number of "critical" joints in the structure which could be monitored. However, there is apparently some disagreement as to whether or not today's platforms even have "critical joints" or what the significance of these cracks are. Another use for these localized techniques could be to use a number of locations to develop a statistical knowledge of the structural fatigue. But there is currently no data to work from in terms of a correlation between minor cracking and fatigue life.

2. Determination of the absolute significance of identified defects to a platform operation or to its structural integrity.

On the first point, all of the research sponsored to date has progressed far in establishing the mean for collection, presentation, and identification of salient features of the data. Depending on the technique, this progress has taken different forms. For instance, better transducers have been developed for acoustic emission work, software and hardware have been developed to extract random decrement signatures, and methods for quantifying changes have been tested, etc. A lot of work has been completed in documenting what is called the "noise rejection" of various techniques. For example, the insensitivity of ultrasonic inspection to simulated barnacle growth or member flooding was established; the ability of acoustic emissions monitoring to separate shaker induced data from cracking, etc., has been shown. Some laboratory techniques have performed well in limited field tests on offshore platforms. Flexibility monitoring tests show that quality data is obtainable at all levels of a platform. Acoustic holography equipment was constructed and tested in a real underwater platform environments.

Now there appears to be a need to go further into actual field environment testing to satisfy all parties and to share that the various techniques can deliver good data in what is perceived as a very difficult environment. The suggestion was made by several meeting participants that a consortium of oil companies might sponsor such field tests. This would keep the base of participation broad, and at the same time allow more private sponsorship of basic research while maintaining low financial risks for the entire industry. It was also proposed that an abandoned offshore platform would be a best test site because structural damage or changes could be made as desired to establish the sensitivity of the techniques.

A few problems were noted in connection with these proposals. One industry representative noted that many oil companies were currently suffering financially and would be reluctant at this point in time to sponsor such tests since their own in-house research is being cut back. The amount of demonstration required to convince oil companies of the capabilities of any device is often substantial and would be a financial drain.

On the second point, it appears that a lot of field work is still necessary. From the research side, the first step is for each technique to establish the connections between the appropriate destruction phenomena observed and actual structural causes. Much progress has been made to date in this area, but more needs to be done. For example, the connection of Random Decrement signature changes to a specific structural change needs to be

Basically, this method would attempt to transfer the reasoning processes of people (who are experts in analyzing various types of structural data) into the complex computer code for crack analysis. This computer code would use a heuristic approach to infer the most probable diagnosis, or at least a set of possibilities. The code could conceivable use many different types of data, for instance, flexibility monitoring and random dec and ultrasonic data from critical joints, analyzing each type subject to its own rules and making the appropriate deductions. ultimately, the program could be packaged and put on a platform permanently.

As part of the general discussion, Mr. Allan Gordon, an attendee from the Naval Ocean Systems Center, brought up some work that he is currently doing under the sponsorship of MMS. Using a 1-meter diameter acoustic lens built by the U.S. Navy, Mr. Gordon is conducting stand-off inspections looking for gross structural defects. The lens is lowered from a barge up to 100 yards away from a structure, and held in place underwater by a set of propulsors. Although work is just beginning, fairly good resolution images of K-joints have been collected.

Finally, a memorandum from a corporation called "G-2 Consultants" a nonparticipant in the conference, was introduced. It concerned a novel NDE method wherein fiber optic cables would be attached to the structure at the time of construction. Structural deformation could be measured by changes in the transmission of light through the fibers.

7 Comments by Sponsors and Industry

During the question and answer periods and general discussions, researchers, government sponsors and industry representatives commented on all areas of current technology and areas for future research and tried to determine how close to commercialization and applications these techniques are.

It appears, from those discussions, that researchers and one hand commercial industries need to work toward common goals in the two basic areas:

1. Demonstration of the abilities of the current techniques in producing repeatable, meaningful data in field environmental uses.

based on analysis of acoustic emissions and has shown the ability to detect 93% of the cracks in welds.

7. Work is being sponsored on development of acoustic emission sensors and characterization of acoustic emission signals, very much like the work described by Dr. Green and Mr. Fuller presented at this meeting.

6.3 Acoustic Holography

As part of this program, Dr. H. Dale Collins of Battelle Northwest gave a presentation on an underwater inspection tool, which was designed, developed and tested a few years ago. The system produces 3-dimensional images of the wall of a pipe or weld material in real time allowing for rapid and sure identification of cracks.

The system consisted of a diver's hand-held "gun" which contains an array of acoustic sensors that can be placed on the pipe surface. The gun also contains a camera and lights for visual reference. Data coming from the sensor array is fed into a computer in the submersible accompanying the diver. This computer generates real time holographic images from the acoustic data.

Dr. Collins emphasized that holographic imaging is a very simple algorithm which should be more widely used. The simplicity of the algorithm is responsible for the fact that a 3-dimensional image can be generated in near-real time.

Dr. Collins sees the next step for this technology as the development of the permanent location of acoustic sensor arrays on platform "hot spots." This will allow continuous monitoring of the structure from the surface. Work needs to be done in reducing the cost of sensor arrays, identifying the "hot spots" for locating the arrays, and developing reliable telemetry for getting the data to the surface for computer generation of the holographic images.

6.4 Other New Ideas

Dr. Shyam Sunder of MIT proposed an idea for research which could incorporate a number of the analysis techniques discussed in the Workshop. The idea is to apply the computer-based expert systems theory, part of the new field of artificial intelligence, to the problem of diagnosing damages in complex structures.

from crack propagation. For this and other reasons acoustic emissions cannot currently successfully distinguish between crack propagation and friction.

Mr. Davies mentioned that segregating emissions that occur at maximum stress or loading could help this problem. It was conceded that this would be possible in the laboratory, but that in a real situation, the complexity of the loading pattern would make it improbable.

6.2 Overview of FHWA Research in Non Destructive Testing

Mr Charles McCogney of the Federal Highway Administration reviewed a number of the developments in NDE made under the sponsorship of FHWA. Their primary focus has been in the development of portable equipment to help bridge inspectors in their regular inspections. The following programs were reviewed:

1. The development of two complementary, hand held tools; an acoustic crack detector and a magnetic crack definer which can be used to examine very localized areas. The acoustic detector can identify the existence of a crack and the distance to a crack, and the magnetic detector can identify the precise location and determine crack length and orientation.

2. Development of an acoustic emission system and program that works on triangulation principles to locate cracks.

3. Development of a magnetic field disturbance system to look for breaks in reinforcing rods in concrete beams. In this method, a set of rails are set up below the concrete beam, and a cart with the magnetic field disturbance instrument rides along them.

4. Work on a tomography system which bombards a metal or concrete sample with radiation and develops a two-dimensional view of the structure. While the basic technology is known and is effective, development of a self contained package that can be handled on a bridge has yet to be commercialized.

5. Development of a residual stress measurement unit. This has been somewhat successful. Unfortunately, the Barkhausen unit developed can only measure surface stresses.

6. An in-process weld monitor has been developed to certify steel welds as the welding is being done. The system is

associated with present acoustic emission sensors. That is many current sensors are highly dampened, broad band devices based on ultrasonic sensor design. Depending on the characteristics of these sensors, their resonant frequencies, etc., and the arbitrary settings of acoustic emission thresholds, one can get widely different characteristics for the same emission. Work currently being done at the National Bureau of Standards and United Technologies has turned out new types of sensors specifically for acoustic emission testing which are great improvements.

Mr. Mike Fuller of Drexel University presented the results of a typical offshore platform K-joint fatigue test in which acoustic analyzed.

That study found acoustic emission amplitudes increased up to a point cracks at which initiation and during crack propagation, then these amplitudes dropped during periods in which crack growth appeared to stop. This finding corroborated previous Drexel University research. Mr. Fuller mentioned that proper settings of the threshold level is very important in making these distinctions.

The study also corroborated the fact that acoustic emission rates are low during crack propagation and higher when growth ceases.

A unique element of this study was that simultaneous to the acoustic emission test, shakers for other vibrational tests and ultrasonic transmitters and sensors were being used. This provided an opportunity to see how acoustic emission testing performs in a noisy environment. The testing showed that shaker data was very low amplitude, high event rate data that could be easily separated from real acoustic emission data.

Finally, some of the data analysis pointed to new features of acoustic emission data that should be examined further. Mr. Fuller presented tentative correlations of pulse duration and pulse amplitude which may imply that pulse duration is a possible indicator of crack propagation.

As for future research, Mr. Fuller would like to see more K-joint tests. The results so far are very encouraging but more confidence must be gained before conclusions can be drawn.

General discussion on acoustic methods were carried out at the conference. Two basic issues were discussed. The first was that the ability of acoustic emission techniques to distinguish between emissions from crack propagation and crack rubbing. Mr. Ray Davies of the Det Norske Veritas noted that the metallurgy of the material was important and that for some materials the amplitude of signals from crack rubbing can be larger than those

Several other areas for future work were identified by Dr. Rose, including development of quality, low cost sensors; determination of critical areas for inspection on offshore structures; and methods for transmitting data from underwater sensors to the surface by means of telemetry.

One final comment to make about the ultrasonic method relates to what Dr. Rose labels as a "global" monitoring technique. This is relative to a highly localized ultrasonic crack detection that is currently in wide use Dr. Rose's new technique can cover a large, complex piece of structure (e.g., an entire K-joint). However, the technique is not "global" in the same sense as the flexibility monitoring or Random decrement analysis which evaluate ar entire offshore platform as a whole.

6 Presentation of Other State-of-the-Art NDE Research

6.1 Acoustic Emissions

Two presentations were made on the characterizations of acoustic emission signals in identifying crack propagation. Dr. Robert Green of Johns Hopkins University outlined some ongoing work on fundamental issues in acoustic wave propagation and sensing.

In this presentation, Dr. Green pointed out that "to be able to characterize acoustic emission signals, the interaction of the emission with the material must be understood." The anisotropic nature of materials in most real structures implies that waves will propagate in irregular geometries. Different frequencies of waves will then alternate in different amounts due to interactions with grain boundaries, dislocations, etc., with the material. Also, an acoustic emission can generate many types of waves simultaneously within the structure. Primarily, there is a bulk shear wave, but there are also surface waves, and possibly lamb and other waves set up in the material. Finally, the geometry of the structure is important.

To attack these propagation problems, Dr. Green has been using a sensitive laser interferometry technique and a highly repeatable wave generation device to measure surface wave propagation. This combination allows him to gain a detail of wave propagation in various materials and geometries.

The other main problem that Dr. Green currently sees is manipulated from the surface. The second effort is the configuration of a system of sensors and hardware specific to the flexibility monitoring task. Finally, more field tests, hopefully in situations where real damage might be detected (e.g., abandoned platforms).

While Dr. Rubin has developed and pursued flexibility monitoring from a very practical basis, Dr. Shyam Sunder of MIT has begun to establish its mathematical basis. This initial work has covered the relationship of modal flexibility to lateral flexibility, the effect of multiple member severances on flexibility parameters, and the influence of measurement errors in estimating flexibility.

5 Ultrasonic Inspection

During the conference, Dr. Richard Dame reported that the ultrasonic methods investigated by Dr. Joseph Rose and his team from Drexel University, performed well in its test sequence of the Round Robin program. The method successfully predicted catastrophic failure of a scaled model of K-joint from a typical offshore platform.

As part of his presentation, Dr. Rose discussed the basic elements of his technique. He reported on work which was done subsequent to the Round Rubin tests and outlined areas for future work.

Dr. Rose described his technique as a feature based methodology. While most forms of ultrasonic inspection rely on measuring the time of flight of an ultrasonic wave to and from a reflector, this method looks at features of ultrasonic waves propagating through a structure.

Work done subsequent to the Round Robin tests investigated issues directly related to the technique's applicability to real offshore platform problems. Tests have shown that simulated marine growth does not affect the technique, nor does running tests in water instead of air. Other tests performed by the group have shown that in some ways the technique can be too sensitive in signaling damage for practical purposes. That is, the similarity coefficients used in the analysis can drop substantially when the structure still has a large percentage of its remaining life. Dr. Rose proposed that setting thresholds which are consistent with the amount of damage one desires to detect is an area for future work.

During the conference, Dr. Dame reported that the frequency monitoring approach also performed very well in the Round Robin test program. Through a combination of global monitoring modes, local modes, and flexibility monitoring, the method identified the occurrence and severity of damage and provided generally accurate locational estimates.

The Aerospace Corporation team headed by Dr. Sheldon Rubin conducted research on the technique and provided very detailed explanations of the reasons for their various test diagnoses.

As with Random decrement, the question of distinguishing between damage and non-damage structural changes was not completely answered by the program. For example, in a test case in which a small amount of damage was inflicted, the Aerospace team's submittal mentioned that the team could not be totally confident that this was not a mass change.

4 Flexibility Monitoring Methods

Dr. Sheldon Rubin, the leader of the Aerospace Research Group, presented the results of work on the flexibility monitoring method's work which was performed subsequent to the Round robin program. Dr. Rubin has identified flexibility monitoring as the most promising frequency response analysis tool for the offshore platform type of structure.

Recent field tests on two offshore platforms have shown that noise from drilling activities does not affect the quality of data for the flexibility monitoring methods. Also, good data was obtained from all levels of the platform, including the very bottom where deflections are small.

The quality of the data from the field tests has led Dr. Rubin and his team to estimate the potential sensitivity of the flexibility monitoring. He expects that complete severance of diagonals which contribute down to 1/6 of bay stiffness in any given direction will be detectable by his new methods.

At this point, a few areas for future work have been defined by Dr. Rubin. The first effort is to lobby for placement of instrument chutes on all new platforms which will allow sensors to be placed anywhere along the platform legs which can be more than accelerometer location. In a manner conceptually analagous to triangulation, signatures derived from various combinations of sensors could provide locational information.

Dr. Yang is also pursuing a system identification approach to this problem. The first step, which is being refined at present, is to generate the mass, stiffness, and damping matrices for a math model of the structure extracted from random decrement data. After this is done, the various coefficients must be identified with specific structural characteristics. The hope is that changes in Random decrement signatures can be related to specific structural causes in this way.

Mr. Henry Cole, credited with inventing the Random Decrement technique, envisions another possible approach. A library of damage signatures could reside in a computer for constant comparison to signatures coming from the actual structure. A match would allow specific identification of a failure listed in the library. Future work would have to decide whether this library is generated through computer simulation or scale model test data, and would try to test out the idea.

In addition to the issue of damage location, work is being done on other aspects of Random decrement, from theoretical foundations to practical application.

At the conference Mr. Henry Cole presented a mathematical and experimental analysis of the relationship between autocorrelation to Random decrement for a variety of situations. He showed that for some simple situations, they generate the same signatures and estimates of damping, but that for a number of more complex situations, they produce very different results.

Mr. Henry Cole, Randomdec Computers Inc. and Dr. Shyam Sunder of MIT discussed the important relationship between input spectra and Random decrement signatures, particularly the effects of non-white noise.

On the practical side, Mr. Peter M. Alea of the NASA Goddard Space Flight Center reported on his experiments with Random decrement and identified two areas for future work. One is the calibration of the similarity coefficient used to quantify differences in Random decrement signatures to levels of damage; and the other is filtering out unwanted modes from test fixtures and uninteresting parts of the structure from the response data.

3 Frequency Response Methods

Three of the major methods which have been supported by ONR and MMS were represented at the meeting:

1. Frequency Response Methods
2. The Random Decrement Method
3. Ultrasonic Inspection Techniques

2 The Random Decrement Method

During the conference Dr. Richard Dame of Mega Engineering presented the results of the Round Robin Test Program. The general conclusion was that the random decrement techniques had performed very well in identifying that damage had occurred to a scale model offshore platform. Further, it had been confident in its diagnosis of low levels of damage, and had reportedly made its judgments using a very minimal sensor network.

The only question raised by the tests was how well Random decrement could locate damage in a complex structure. The University of Maryland team, headed by Dr. Jackson Yang, investigated Random decrement method in the program, gave good indications of damage occurrence but only tentative estimates of the damage locations. They were not able to provide detailed rationale for these locations judgements. Research into Random decrement's capabilities along this line are continuing, but the Round Robin tests themselves left the locating capabilities unsubstantiated.

Also unanswered by the Round Robin test program were questions about the ability of Random decrement (and other vibrational analysis methods) to differentiate between the changes in structural vibration characteristics caused by damage, from those caused by marine growth, platform equipment noise, and deck mass changes. The Round Robin test program did not attempt to simulate these potentially confusing situations.

A few ideas for refining Random decrement's ability to locate and specify damage in complex stuctures are currently being pursued or are seen as fruitful for future research.

Dr. Jackson Yang and his team at Maryland University are currently investigating "cross-random signatures" as one possible method. These signatures are generated from data coming from

AN OVERVIEW OF THE CONFERENCE

1 Background

In 1982, a series of Nondestructive Evaluation (NDE) Program Tests, sponsored by the Office of Naval Research (ONR) and the Department of Interior, Minerals Management Service (DOI, MMS), were conducted to determine the ability of several nondestructive test methods to detect failures in a "blind mode." These tests were conducted by an independent test agent and were used to compare the success or failure of different testing methods to predict when damage had been inflicted to a laboratory test structure.

At the conclusion of this program, it was decided by the sponsors that a workshop should be conducted to assess the general success or short falls with current State-of-the-Art NDE methods.

In January 1983, a two day working meeting was held in Reston, Virginia, to review this progress. An overview summary excerpt of these proceedings follows. The summary of all proceedings are in an Appendix to this report.

The Workshop presentations and discussions centered on three major themes:

1. Analysis of activities which have been sponsored by ONR and MMS, including reviews of recent efforts, updates on current research, and discussion of areas of future work.

2. Presentation of State-of-the-Art developments and research in other NDE methods.

3. Assessment by researchers, industry representatives, and research sponsors of what actions are still needed in order to bring these NDE methods into commercial application.

1.1 Analysis of ONR & MMS Sponsored Activities:

APPLICATION OF ACOUSTICAL HOLOGRAPHY TO THE INSPECTION OF OFFSHORE PLATFORMS

Dr. H. Dale Collins
Battelle, Pacific Northwest Laboratories

This paper describes a diver operated underwater optical-acoustical imaging system for the inspection of internal defects in offshore platform weldments. The two-dimensional acoustic array is electronically programmed with digital techniques to simulate focused and non-focused source-receiver scanning. The electronic simulated reference beam is programmable using erasable proms. The imaging device consists of a diver hand held gun containing the acoustic array, miniature television camera and the L.E.D. display array. The gun is connected via the diver pack and cable to the control unit, digital memory display and data recording units located in the submersible. The television camera provides an optical view of the external weld surface, identification marks, etc., which is integrated with the acoustical image on a standard television monitor. The acoustical array provides complete real-time inspection by electronically scanning and constructing multiple focused holograms through the entire weld volume. The defect images are presented in side, plan and pseudo three-dimensional views with the options of rotation, tilt and zoom magnification. The system has two permanent recording techniques: the focused holographic defect images and optical views are stored on videotape and the basic r-f data on digital tape. This paper presents the results obtained during the laboratory trials, thus illustrating the unique capabilities of the system in flaw detection, location and sizing. This system has been tested in the North Sea by International Submarine Services.

UNDERWATER USE OF RADIOGRAPHY
AND ULTRASONICS

(CANCELLED)

David Raacke
Owensby & Kriticos, Inc.

The use of radiographic and ultrasonic inspection methods in the underwater environment is not something spectacular or mystical. It is the extension of accepted and proven techniques. The equipment used in some inspections is the same as that used in topside methods. This is not to imply that the underwater use of radiography and ultrasonics is simple, but with the application of some basic techniques, underwater NDE is very reliable.

Of the two methods, underwater radiography is closest to standard surface inspection techniques. An additional benefit is actually gained in a great reduction of radiation exposure to the personnel involved. This is because the X-ray absorption of water, particularly sea water, is far greater than that of air. The actual techniques and practices in the photography are affected very little by the water environment.

In the case of underwater ultrasonics, even though the actual inspections may parallel those used normally, special training and procedures are required. Without this pre-project setup, underwater ultrasonics can be a disaster. This is true whether a topside technician only or a technician diver is relied upon for the inspection process interpretation.

OWENSBY & KRITIKOS, INC. has found that in underwater inspection, there are several important factors: the proper cleaning of the area to be inspected; the proper planning of which areas are to be inspected and how thay are to be inspected; and the proper interpretation of results. The most essential item in underwater inspection, or any inspection, is properly trained personnel. Without personnel who are experienced in working in this type of environment, underwater radiography and ultrasonics are of no good to anyone. However, when a properly planned and conducted underwater inspection is made, whether it be for a monitoring procedure or for a repair condition, radiography and ultrasonics are valuable tools in the nondestructive evaluation industry.

ACOUSTIC EMISSION SOURCE LOCATION AND IDENTIFICATION

Robert E. Green, Jr.
Johns Hopkins University

Although the phenomenon of acoustic emission has been the subject of an ever increasing number of scientific investigations and technological applications for more than 20 years, it has not optimally fulfilled its promise as a non-destructive testing technique since the precise characteristics of the stress waves emitted from specific sources remain unknown. It is the purpose of the present work to describe how analysis of the elastic waves emitted from an acoustic emission source, coupled with analysis of their propagational behavior through the workpiece, is necessary in order to properly locate and identify the source of the acoustic emission signals. Experimental results will be presented which use acoustic emission sources possessing known features, specimens of controlled geometry, novel piezoelectric transducers and laser interferometric probes to verify the analytical considerations.

AN ANALYSIS OF ACOUSTIC EMISSION DATA ACQUIRED FROM A 1/3 SCALE MODEL K-JOINT FATIGUE TEST

Michael D. Fuller and Joseph L. Rose
Drexel University

Jim Mitchell and John Crowell
Physical Acoustics Corporation

Charles McGogney
Federal Highway Administration

Acoustic emission technology is relatively new, however, the present state-of-the-art has warranted consideration of an acoustic emission technique for monitoring the integrity of offshore structural joints. Many laboratory experiments have been conducted to date, which indicate that the fatigue damage in various materials may be successfully monitored. Most studies consider only relatively simple geometries in a very controlled environment. Structural joints in offshore platforms offer complex geometries in uncontrolled environments in which emissions generated form cracks must be considered along with emission from random sources and platform equipment.

To investigate the feasibility of acoustic emission for application to offshore platforms, a 1/3 scale model of a structural K-joint was instrumented with 150 KHz resonant sensors. (The K-joint was also instrumented for ultrasonic evaluation and the acquisition of strain and vibration data.) The K-joint was loaded sinusoidally in a unidirectional fashion, fatiguing the structure to failure. The experiment was conducted without providing special precautions to the acquisition of acoustic emission data. As a result, ultrasonic and vibration testing, along with other random emitters, served as an excellent simulation of possible contamination that might be expected in an offshore environment.

Data obtained form the fatigue testing of the K-joint was highly contaminated with ultrasonic transmission. However, analysis of the data has indicated formation and propagation of fatigue crack damage in this complex geometry. In addition, careful examination of the data allowed identification of the contaminating events.

Data taken from the K-joint experiment displays several additional interesting characteristics which encourage further study. Future work should include signal characterization and recognition. Initial data seems to indicate this analysis is feasible and points to further consideration of acoustic emission for practical implementation on offshore structures.

inspection. A sinusoidal load was applied to the structure, producing cracks (dye penetrant verified) at 75,000 cycles, which were confirmed by the ultrasonic global inspection procedure. The cracks continued to propagate in a uniform fashion, noting similarity coefficient changes during the test, until the K-joint was grossly overloaded to facilitate total failure at 176,000 cycles.

Although fatigue tests to date have been conducted with only the test structure in air, tests on a 1/3 scale model in water shows that the single negative effect appears to be a .12 dB/cm additional attenuation loss. Barnacle growth, simulated by applying clay to the perimeter of the model, resulted in an additional .06 dB/cm loss. It is anticipated, therefore, that technology transfer to actual field structures could take place reasonably well and problems in cabling and data transfer, as well as actual transducer mounting, are solved in a practical sense.

LONG WAVELENGTH ULTRASONIC INSPECTION PRINCIPLES FOR THE GLOBAL EVALUATION OF OFFSHORE STRUCTURES

Joseph L. Rose and J. Bruce Nestleroth
Drexel University

The catastrophic collapse of several offshore platforms has spurred the development of nondestructive inspection techniques for offshore structures. Traditional ultrasonic inspection procedures would require a tedious, time consuming, and expensive local inspection of every tubular joint. An alternative ultrasonic technique has therefore been developed that utilizes a global inspection system designed to give an early warning of damage initiation in a structural joint. The global inspection technique employs long wavelengths, lamb waves, and a similarity coefficient. The method has been successfully tested on scaled versions of K-joint structures, the final test being a fatigue test on a 1/3 scale structure where cracking of a tubular joint was detected as the test was being conducted.

The task of developing a global ultrasonic inspection system for the K-joint required that the physics of low frequency ultrasonics be studied. Implementation of a test protocol on a microprocessor based inspection system was successful. The system makes use of a through-transmission test system with transducers of center frequency less than 1.0 MHz. The transducers are designed to excite an ultrasonic wave that propagates around the casing of the K-joint using the inner and outer walls as wave guides, thus flooding the entire inspection zone (area between the transducers) with sound energy, the nature of the wave being a lamb wave that varies in propagational behavior as a function of the wavelength to pipe thickness ratio. While catastrophic failure of the K-joint will result in total disruption of the received signal (hence damage detection), sensitivity to much smaller cracks may be obtained by utilizing a similarity coefficient analysis.

A 1/3 scale model of a K-joint was prepared for fatigue testing in cooperation with the Goddard Space Center. Five ultrasonic transducer locations were selected for the global

NDE TESTING PROGRAM STATE-OF-THE-ART AT THE FEDERAL HIGHWAY ADMINISTRATION

Mr. Charles McGogney
Federal Highway Administration

The Federal Highway Administration, Office of Engineering and Highway Operation Research and Development, has surveyed approximately fifteen NDE methods for material inspection and testing, ten of which show some promise of success for application on highway bridge components. Of the ten considered, the FHWA has funded research studies and, in some cases, developed instrumentation for inspection and test purposes. Notably the work in ultrasonic, acoustic emission and magnetic field disturbance methods shows good potential. Other methods for residual stress measurements such as Barkhausen noise analysis and acoustic bi-refringence need more research.

THE APPLICATION OF THE RANDOM DECREMENT SIGNATURE TECHNIQUE TO A K-JOINT STRUCTURE DURING FATIGUE TESTING

Peter M. Alea
NASA Goddard Space Flight Center

The recent K-joint fatigue test provides a unique opportunity for the Structural Dynamics and Electromagnetic Test Section at the Goddard Space Flight Center to evaluate the ability of the Random Decrement Signature (RDS) technique to detect the onset of failure in a complex structure.

The strategy is to obtain an RDS for a set of structural mode shapes that is expected to be influenced by the occurrence of a failure. The structure of interest is loaded for a period of time and subsequent RDS's are extracted. These RDS's are correlated with respect to an initial (baseline) signature that is indicative of the structure in an undamaged state. Variations in the correlation coefficient are then an indication of structural degradation.

A progress report with the latest technical results from the K-joint fatigue test will be presented. The sensitivity of the RDS technique for detecting the initiation of failure and for subsequently monitoring the crack growth in the K-joint will be discussed.

DETECTION OF DAMAGES WITH SYSTEM IDENTIFICATION

Dr. Jackson C. S. Yang
University of Maryland

The random vibrational response of a structural system contains the characteristic signal of the structure. Using proper signal processing techniques, the characteristic signal can be retrieved from the random response. Structural damages can then be identified by studying the changes of the characteristic signal.

Two signal processing techniques are being used by us to retrieve the structural characteristic signal from the random responses. The first is in the frequency domain, using the FFT technique to obtain the averaged frequency response of the system. Followed by a curve-fitting computer program, the system's eigenvalues and eigenvectors are resolved from the frequency response curves. The second is the random decrement technique, in which the random response is converted to the random decrement signature. Using an auto-regressive method, the system's eigenvalues and eigenvectors can be determined from the random decrement signature.

Cross random decrement signatures between two positions correlate the random responses of the two. If an array of cross random decrement signatures between a number of positions in the structure is evaluated, the location of the damage can be determined following proper system identification processes.

The system identification technique we adopt at the present time, uses a state equation formulation, where the system's eigenvalues and eigenvectors are reduced to the mass, stiffness and damping matrices. The changes of the matrix elements will provide the indication of the location and severity of the structural damage.

RESEARCH TOPICS IN FLEXIBILITY MONITORING

Dr. S. Shyam Sunder
Massachusetts Institute of Technology

The presentation focusses on current and contemplated research at MIT on flexibility monitoring inspection. Topics addressed include the following major issues:

(a) Theoretical basis for the flexibility monitoring concept.

(b) The influence of multiple member severances on damage predictions.

(c) Sensitivity of the "flexibility" parameter to uncertainties in modal identification.

(d) Development of a computer-based damage assessment system based on the knowledge-based expert systems theory of artificial intelligence for prototype implementation of flexibility monitoring inspection.

FLEXIBILITY MONITORING INSPECTION
OF FIXED OFFSHORE PLATFORMS

Sheldon Rubin
The Aerospace Corporation

A new concept, called Flexibility Monitoring, has been devised to detect failures in steel jackets, and in their foundations, that are of significance to overall strength. The technique involves detection of the mode shapes of the fundamental sways and torsion from ambient vibrations. Flexibility Parameters, which relate closely to the shear flexibilities of each jacket bay and of the foundation, are determined from these shapes. These parameters, when compared to baseline data are the basis for assessment of possible jacket damage - most notably severence of diagonals in a vertical face - and assessment of significant damage or change of the foundation. The approach is relatively insensitive to deck mass and marine growth changes.

The practicality and accuracy of the method has been assessed in the Round Robin laboratory test program and in two recent field tests on Gulf of Mexico platforms, Shell Cognac and Chevron Garden Banks. The field testing involved underwater positioning of accelerometer packages at a sequence of levels via abovewater accessible chutes attached to corner legs.

It is believed that a realistic goal for the sensitivity of the method, when implemented operationally, is to detect the severance of a single diagonal that accounts for at least 1/6, and possibly 1/8, of a bay shear stiffness in the affected sway direction.

ROUND ROBIN TEST PROGRAM RESULTS

Dr. Richard E. Dame
Mega Engineering

The Round Robin Test Program was undertaken to document the abilities of several non-destructive evaluation (NDE) techniques in monitoring the integrity of large, complex structures. The program was funded jointly by the Office of Naval Research and the Minerals Management Service, Branch of Technology Assessment and Research, of the Department of the Interior.*

The test program required advocates of various techniques to diagnose damages done to a scale model offshore oil platform. These diagnoses were based on data acquired by an independent test facility which carried out the specific instructions of the advocates in applying the techniques. In this way the advocates were blind to any information on the exact nature of the damages except for the data provided by their instrumentation.

Of the three NDE methods which completed the testing (two others dropped out during the program), the Random Decrement Technique and the Frequency Response Technique both showed the ability to determine whether or not structural damage had occurred and to estimate the severity of that damage. Beyond that, the Frequency Response Method performed best in locating the damage and the Random Decrement Method showed more confidence in identifying low levels of damage. In a seperate test sequence, the Ultrasonic Technique demonstrated the ability to predict impending catastrophic failure in a scale model welded steel K-joint.

*What was formerly the Conservation Division of USGS is now the Minerals Management Service of the Department of the Interior due to a recent reorganization of DOI.

PRE-CONFERENCE ABSTRACTS

WARREN, Harry A.
Mega Engineering
10800 Lockwood Drive
Silver Spring, MD 20901
(301)681-6903

WINTER, John
Mat'ls. Science & Engineering Dept.
Johns Hopkins University
34th & Cahrles
Baltimore, MD 21218
(301) 338-7152

YANG, Dr. Jackson C. S.
U. of Maryland
Mechanical Engineering Dept.
College Park, MD 20742
(301) 454-7375

GREGORY, Mr. John
U. S. Dept. of Interior
Minerals Management Service MS-647
12203 Sunrise Valley Drive
Reston, VA 22091
(703) 860-7865

JIANG, Dr. Jumping
Univ. of Maryland
Mechanical Engineering Dept.
College Park, Maryland 20742
(301) 454-7375

JOHNSON, Duane
Failure Analysis Association
2225 E. Bayshore Rd.
Palo Alto, Calif. 94303
(415) 856-9400

KAO, Carl S.
Mobil Res. & Devel. Corp. - P.O Box 345100
Farmers Branch, Texas 75234
(214) 851-8339

KNAPP, A. E.
Amoco Production Co.
P. O. Box 591
Tulsa, Okla. 74102
(918) 660-3598

LEW, H. S.
Nat'l Bur. Standards
Ctr. for Bldg. Technology
Bldg. 226, Room B162
Washington, D. C. 20234
(202) 921-2647

LIGHT, Harry
HQ DARCOM
Attn: DRCQA-EQ
5001 Eisenhower Ave.
McLean, VA 22333
(202) 274-8916

MASTANDREA, John R.
NDE Technology, Inc.
2909 Oregon Ct., C-8
Torrance, Calif. 90563
(213) 320-5782

MATZEN, Prof. Vernon C.
No. Carolina State U.
Sch. of Engineering
P. O. Box 5993
Raleigh, N. C. 27650
(919) 737-2331

McGOGNEY, Charles
HRS-11
Federal Highway Adm.
Washington, D. C. 20590
(703) 285-2072

MOOK, Dean
Office of Naval Research
Code 432
800 No. Quincy St.
Arlington, VA 22217
(202) 696-4305

PERRONE, Nicholas (Retired)
12207 Valerie Lane
Laurel, MD 20708
(301) 776-4226

ROSE, Prof. Joseph L.
Drexel Univ.
Dept. of Mech. Eng. & Mechanics
Philadelphia, PA 19104
(215) 895-2295

RUBIN, Dr. Sheldon
The Aerospace Corp.
3531 Alara Dr.
Sherman Oaks, Calif. 91403
(213) 648-6408

SMITH, Mr. Charles
U. S. Dept. of the Interior
Minerals Mgmt. Service
MS 647
Reston, VA 22091
(703) 860-7865

SPENCER, Jack C.
Marine Tech. & Hazardous Mat'ls Div.
Commandant (G-MTH-4/13) U.S.C.G. Hq.
2100 Second St., S. W. Rm 1300
Washington, D. C. 20593
(202) 426-2197

SUNDER, Shyam
M. I. T.
Dept. of Civil Engineering Rm 1-274
Cambridge, Mass. 02139
(617) 253-7118

TSAI, Dr. Tsunming
U. of Md.
Mechanical Engineering Dept.
College Park, MD 20742
(301) 454-7375

PARTICIPANTS
NONDESTRUCTIVE EVALUATION METHODS WORKSHOP
January 1983

ALEA, Mr. Pete
NASA Goddard Space Flight Ctr.
Code 754.1
Greenbelt, MD 20771
(301) 344-5410

BASDEKAS, Dr. Nicholas
Office of Navel Research
Structural Mechanics Program
Code 432
800 No. Quincy St. - Rm 619
Arlington, VA 22217
(202) 696-4307

BOLELHO, Mr. D. L.
Chevron Oil Field Res. Co.
P. O. Box 446
La Habra, Calif. 90631
(213) 694-9160

CAMPBELL, Mr. Brad
Exxon Prod. Research Co.
P. O. Box 2189 Pt-1560
Houston, Texas 77001
(713) 940-3757

Carino, N.J.
National Bur. Standards
Bldg. 226, Room B-162
Ctr. for Building Technology
Washington, D. C. 20234
(202) 921-3128

CHEN, Jay C.
Jet Propulsion Lab. (MS 157-316)
4800 Oak Grove Dr.
Pasadena, Calif. 91109
(213) 5354-0740

CHEN, Dr. Jieien
U. of Maryland
Mechanical Engineering Dept.
College Park, MD 20742
(301) 454-7375

CHEN, Roger
Advanced Technology & Research, Inc.

(301) 422-8096

COLE, Mr. Henry
Randomdec Computers, Inc.
84 Alvarado Avenue
Los Altos, CA 94022
(415) 941-2399

COLLINS, Dr. H. Dale
Battelle NW
P. O. Box 999
Richland, Washington 99352
(509) 375-2726

DAME, Dr. Richard E.
MEGA Engineering
10800 Lockwood Drive
Silver Spring, MD 20901
(301) 681-6903

DAVIES, Ray
Det Norske Veritas
Independent Testing Labs
P. O. Box 657
Searcy, ARkansas 72143
(501) 268-1475

DYHRKOPP, Felix
U. S. Minerals Management Service
3301 N. Causeway Boulevard
Metairie, Louisiana 70002
(504) 837-4720

FARRAGUT, Nelson J.
NASA/GSFC, Code 741.1
Greenbelt, MD
(301) 344-5907

FULLER, Michael
Drexel University
Philadelphia, PA 19104
(215) 895-2295

GIANGERELLI, Mr. Richard
Minerals Management Service, MS 647
Dept. of the Interior
12203 Sunrise Valley Dr.
Reston, Va. 22091
(703) 860-4490

GORDON, Mr. Allan
Ocean Engineering Dept. Code 9411
Naval Ocean Systems Center
San Diego, CA 92152
(714) 225-6686

GREEN, Prof. Robert E.
Johns Hopkins University
Materials Science and Engineering Dept.
Baltimore, MD 21218
(301) 338-7126

Agenda
Tuesday, January 25, 1982

8:30 Coffee

9:00 Long Wavelength Ultrasonic Inspection Principles for the Global Evaluation of Offshore Structures
Dr. Joseph L. Rose, Drexel University
A method for monitoring an entire K-joint with long wavelength ultrasound has been tested successfully in the laboratory.

9:40 Analysis of Acoustic Emission Data Acquired During a 1/3 Scale Model K-Joint Fatigue Test
Mr. Michael D. Fuller, Drexel University
Results are presented, and events of random acoustic contamination during testing are examined. Trends in AE data are presented for comparison to actual visual inspection and fatigue life of the K-joint.

10:00 Coffee

10:10 Acoustic Emission Source Location and Identification
Dr. Robert E. Green, Jr., Johns Hopkins Univ.
Present work is aimed at describing how analysis of the elastic waves emitted from an acoustic emission source, coupled with analysis of their propogational behavior through the workpiece, is necessary to properly locate and identify the source.

10:50 Underwater Use of Ultrasonics and Radiography
Mr. David Raacke, Owensby and Kriticos
(CANCELLED)
Underwater use of radiographic and ultrasonic inspection methods, although using special procedures, are extensions of accepted and proven NDE techniques. With the essential ingredient of personnel who are properly trained for these applications, these underwater techniques are valuable NDE tools.

11:30 Lunch

1:00 Application of Acoustic Holography to the Inspection of Offshore Platforms
Dr. H. Dale Collins, Battelle Pacific Northwest Labs
A system has been tested in the North Sea which uses a diver operated underwater optical-acoustical imaging system for the inspection of internal defects in offshore weldments. The defect images are presented in side, plan and pseudo three-dimensional views with the options of rotation, tilt and zoom magnification.

1:45 General Discussion

2:30 Adjourn

1:00 Random Decrement Methods
Dr. Jackson C. S. Yang, University of Maryland

1:40 The Application of the Random Decrement Signature Technique to a K-joint Structure During Fatigue Testing
Mr. Peter Alea, NASA Goddard Space Flight Center

A recent K-joint fatigue test provided an opportunity to evaluate the ability of the Random Decrement Technique to detect the onset of failure in a complex structure. The sensitivity of the technique in detecting the initiation of failure and for subsequently monitoring the crack growth in the K-joint will be discussed.

2:20 Coffee

2:40 Comparison of Autocorrelation to Random Decrement Signatures
Mr. Henry Cole, Randomdec Computers Inc.

The mathematical relationship between the Random Decrement Signature and the Autocorrelation function will be discussed as well as comments on the applications of the Random Decrement technique.

3:00 NDE Testing Program State-of-the-Art in the Federal Highway Administration
Mr. Charles McGogney, Federal Highway Administration

The FHWA Office of Engineering and Highway Operation Research and Development has surveyed approximately fifteen new NDE methods for materials inspection and testing, ten of which show some promise of success for applications on highway and bridge components.

3:40 General Discussion

5:00 Adjourn

Workshop on Non-destructive Evaluation (NDE) Methods for Structures

Agenda

Monday, January 24, 1983

8:30 Coffee

9:00 Welcome and Introduction of Sponsors
Dr. Richard E. Dame, Mega Engineering

9:05 Remarks by Sponsors
Dr. Nicholas Basdekas, Office of Naval Research
Mr. Charles Smith, DOI Minerals Management Service

9:15 Round Robin Test Program Results
Dr. Richard E. Dame, Mega Engineering
Laboratory testing on scale models of an offshore platform and a K-joint demonstrated the capabilities of Frequency Monitoring, Random Decrement, and Ultrasonic NDE techniques.

9:30 Flexibility Monitoring Inspection of Fixed Offshore Platforms
Dr. Sheldon Rubin, The Aerospace Corporation
The practicality and accuracy of this new method has been assessed in a laboratory test program and in two recent field tests on Gulf of Mexico platforms.

10:10 Coffee

10:20 Research Topics in Flexibility Monitoring
Dr. Shyam Sunder, MIT
Research is being conducted on the theoretical framework of flexibility monitoring, the influence of multiple member severances on damage predictions, and the sensitivity of the "flexibility" parameter to uncertainties in modal identification.

11:00 General Discussion

11:30 Lunch

INTRODUCTION

The following proceedings were compiled for the Workshop on Nondestructive Evaluation Methods for Structures held on January 24 and 25, 1983 at the Marriott Hotel at Washington D.C.'s Dulles Airport. The workshop was organized by Mega Engineering of Silver Spring, Maryland, and was sponsored by the Office of Naval Research and the Minerals Management Service of the Department of the Interior.

The purpose of the Workshop was to bring together people whose research had previously been sponsored by ONR and MMS, as well as other people currently doing work in NDE, to discuss the state-of-the-art in NDE, areas for future research, and commercial applications. Speakers included members of the academic community, researchers from private laboratories and consulting firms, and representatives from government research projects. Attendees, who numbered about 40, also included representatives from the oil industry, private firms developing NDE techniques, and government offices administering research funds.

These proceedings were abstracted from verbatim transcripts of the presentations and discussions occurring at the Workshop. While maintaining faithfulness to the content of the transcript, Mega Engineering has edited the material to eliminate certain procedural discussions and to clarify the text where errors and omissions in the transcript were evident.

In addition to editing the transcripts, Mega Engineering has integrated, wherever possible, copies of the overheads and slides used by the speakers into the text of their presentations. However, certain speakers were not able to supply such material.

These proceedings also contain lists of names and addresses of all speakers and attendees.

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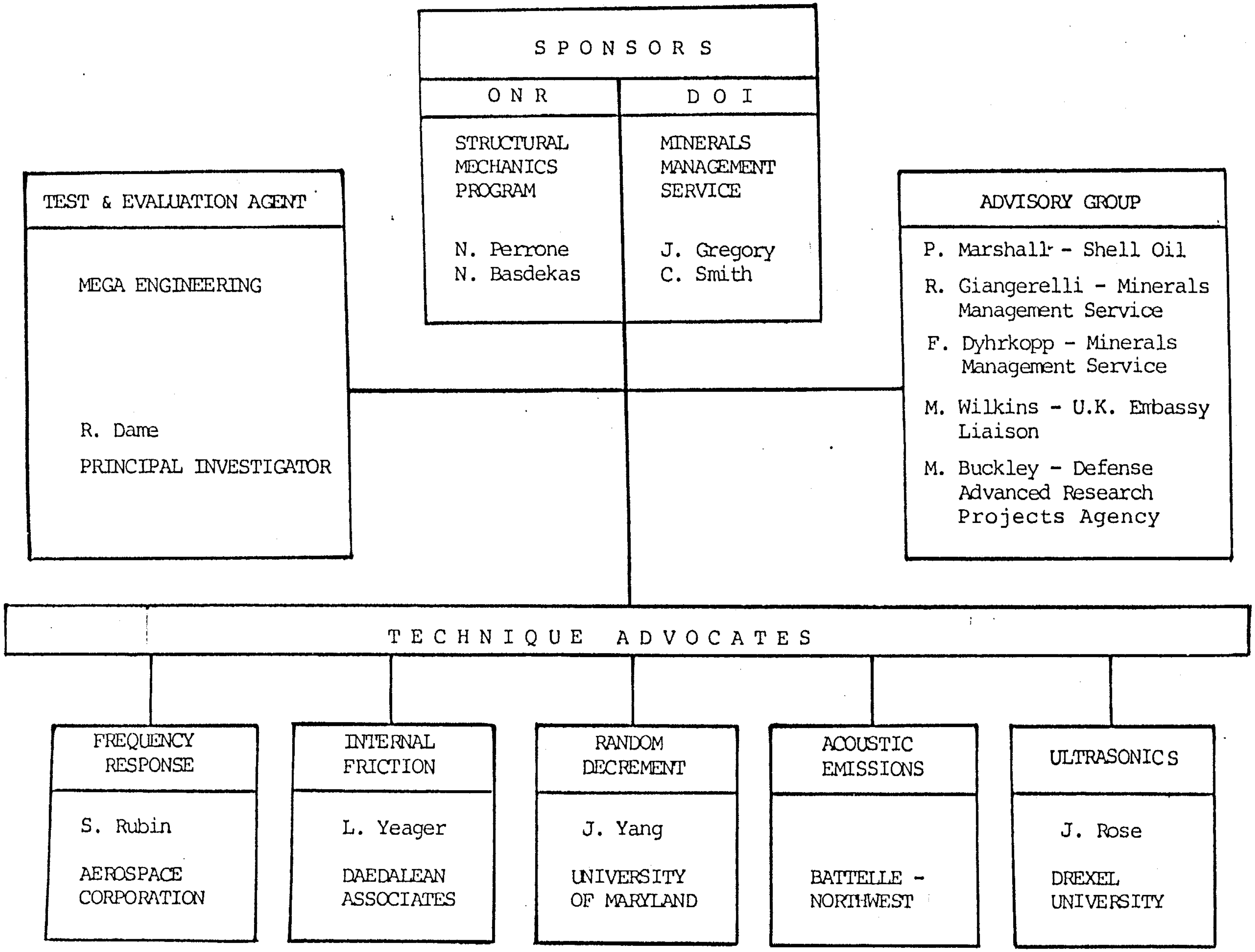
WORKSHOP ON NONDESTRUCTIVE EVALUATION
METHODS FOR STRUCTURES

January 24-25, 1983



NDE ROUND ROBIN ORGANIZATIONAL CHART

FIGURE 3

As part of our project, an advisory group of Advocates and Sponsors provided us with information and worked with us in a series of working meetings to plan and prepare all of the tests. They did not select the damage modes, however.

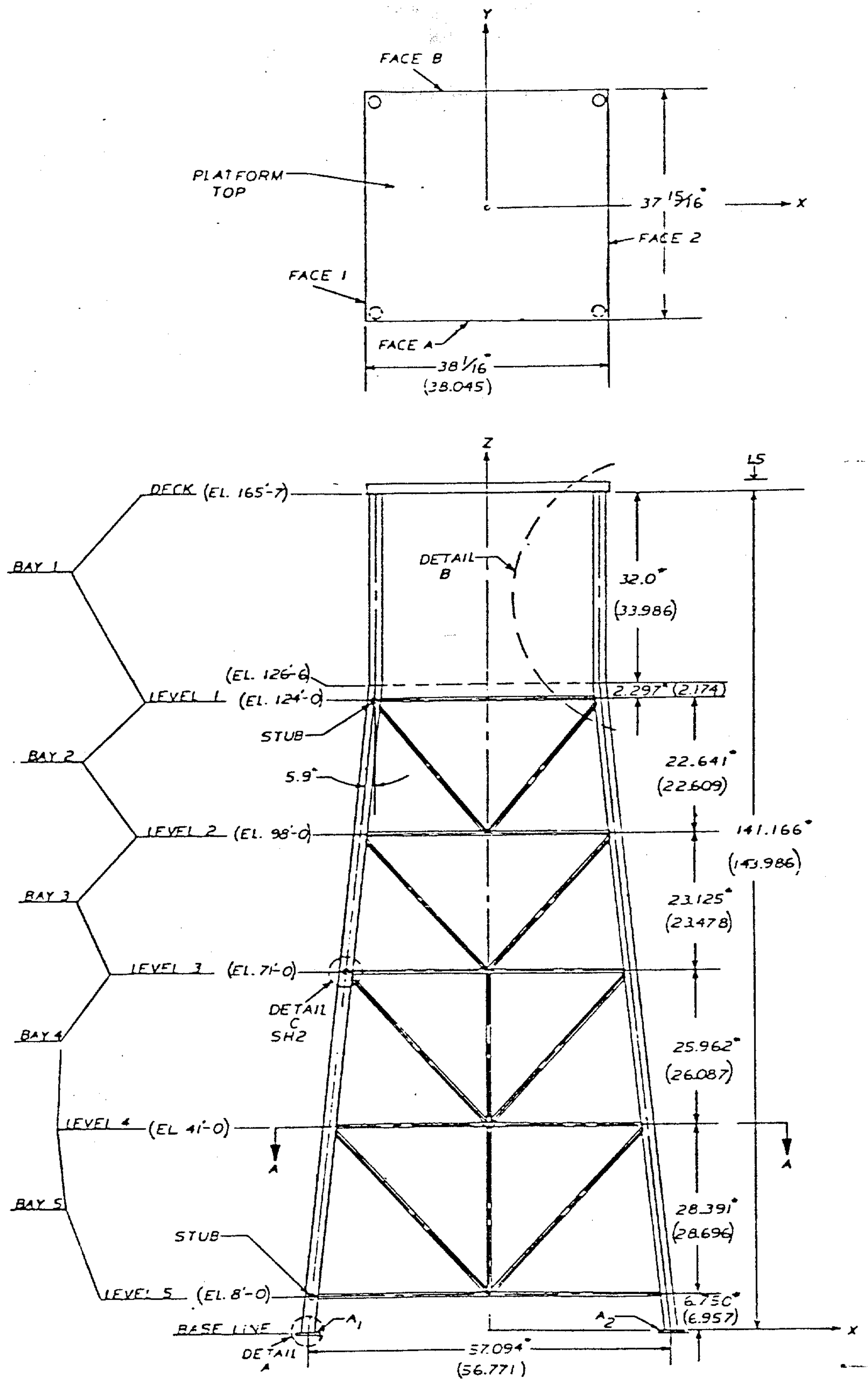
Mega coordinated the project with the sponsors and determined types of tests we would carry out, the results we wanted, and the test sequence.

Initially, there were five techniques involved at: (1) The Frequency Response Technique, advocated by the Aerospace Corporation, with Dr. Sheldon Rubin as the Principal Investigtor of that technique; (2) Internal Friction Monitoring, sponsored by the Daedalean Associates, Frederick, Maryland, with Mr. Larry Yeager as Principal Investigator; (3) a Random Decrement Technique, which was being developed and advocated by Dr. Jackson Yang at the University of Maryland; (4) an Acoustic Emissions Technique, conducted by Batelle Northwest with the Federal Highway Administration under Mr. Charles McGogney's sponsorship, and; (5) the Ultrasonic Technique developed by Dr. Joseph Rose of Drexel University.

Of these five groups, only three finished the testing series. The internal friction monitoring testing was dropped from evaluation when it was found that the technique was not compatible with this blind mode method of testing, which leaves open the question of the validity of that technique. No further consideration was given to that method during the rest of the testing. In the acoustic emissions test, we had a problem scheduling people from the Federal Highway Administration at times when tests could be arranged. When a fatigue test is going on a structure, with the other participants and facilities set up and ready to go, you start cycling this structure, and if someone can't participate at this point, you have to drop them. So that is what happened to that (FHA) group. They were picked up later, I understand, in a series of tests conducted on similar structures.

Figure 4 shows the model structure. This scale model was used in all the piggyback testing for all the NDE candidates, with the exception of the ultrasonic technique.

The ultrasonic technique (Drexel University test) was evaluated as a parallel effort test on a scaled model of a "K-joint", typical of an offshore platform structure joint.



FACE A
(FACE B OPPOSITE)
1/13.8 SCALE MODEL OFFSHORE PLATFORM

SCALE: 1/8

"—AVERAGE MEASURED DISTANCE
( )—U OF MD. DWG. DIMENSION

SCALE MODEL PLATFORM

FIGURE 4

Figure 5 shows the form we used to request data and plans from each of the principals. Each was asked to prepare a series of test plans; these plans included information needed in terms of shaker location, number of accelerometers, instrumentation, and the exact test procedure to be used. This information was coordinated with all of the test advocates and with the testing facility to determine whether there were compatability problems.

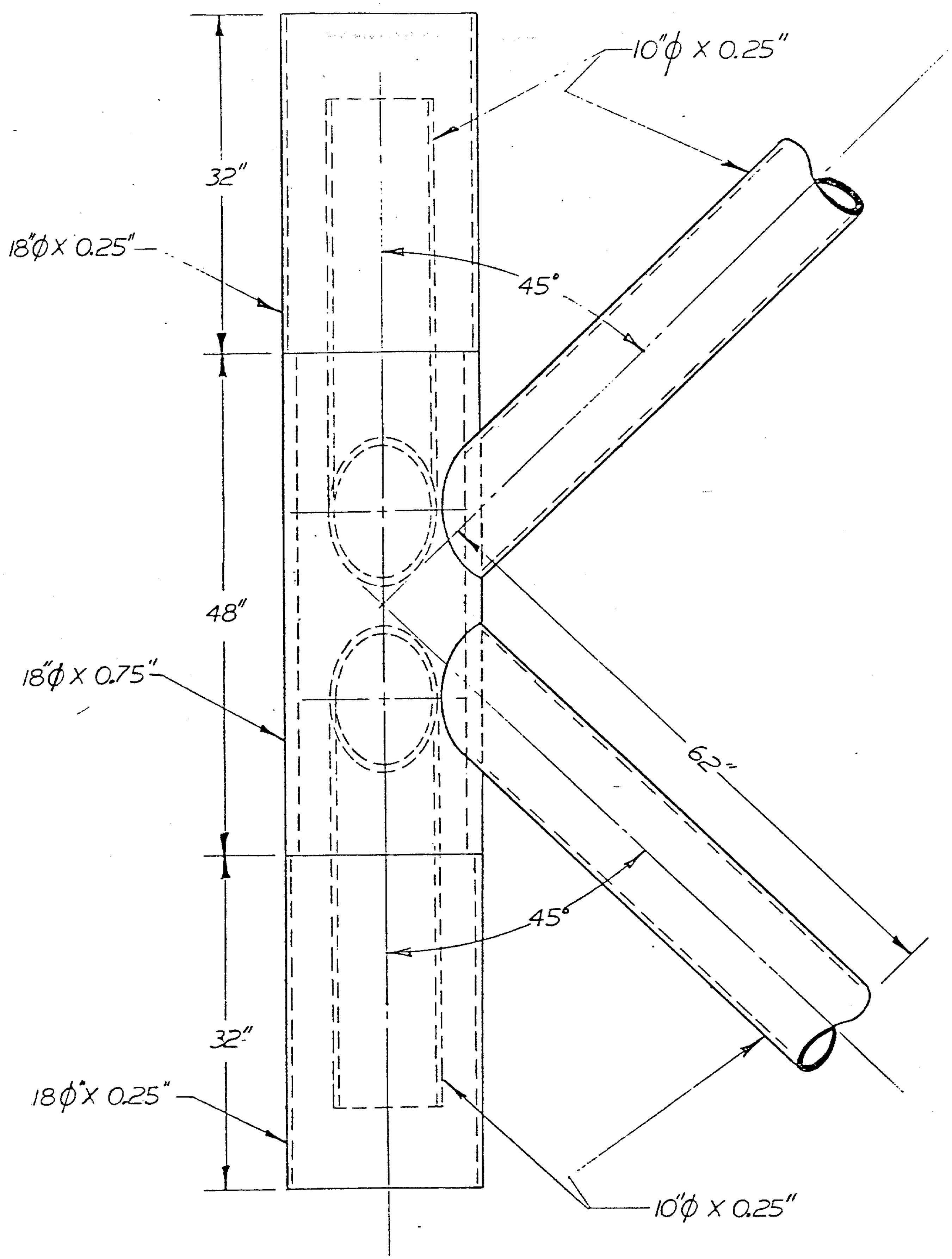
When we finished the assignment of instrumenting accelerometer locations on the structure, we found that close to every member in the structure was instrumented by at least one advocates instrumentation, which meant that on each and every leg and diagonal, we had a piece of instrumentation for everyone of the advocates. So if we began to cut legs or other elements in order to degrade the structure, one of the advocates was going to know for sure and would have an unfair advantage over the others.

Fortunately, about that time, one of the advocates, Daedalean Associates, was dropped giving us some open room for cutting members without direct detection.

Figure 6 reviews the test plans we finally prepared. We began a series of evaluations to assess how complicated the test plans were. If they were so complicated that they couldn't be carried out by independant agents, other than by the advocates, we wanted to try to rank that as part of the program findings. So the number of accelerometers, the complication of the test plans, and whether or not these test plans were going to be modified after the program was under way, were all points to consider.

We were constrained in the testing. As I said before, the location of sensors severely limited the types and numbers of tests.

Most of the test procedures offered by the advocates were so complicated that they could not be run simultaneously. Rather, they had to be run separately. That is, we would run one test, stop, recalibrade, set up again, and run another series of tests for a different advocate. This was costly, time consuming, and used up a large portion of the budget, and finally limited the number of tests which could be run. Before we inflicted any damage to the structure, a complete series of "baseline tests," was run for each advocate which was the benchmark given to the advocates against which they would look for changes in the structure. We were led to believe by the advocates that each of the techniques were so sensitive, that they could pick up any



SCALE MODEL K-JOINT

FIGURE 5

ASSEMBLY OF TEST PLANS

- ADVOCATES DEVELOPED INDIVIDUAL TEST PROCEDURES AND SENSOR LOCATIONS

- ALL SENSORS WERE LOCATED ON MODELS AND TEST PROCEDURES WERE INTEGRATED INTO ONE PLAN

- PROBLEMS

  - SENSOR LOCATIONS SEVERELY LIMITED TYPES OF DAMAGE ALLOWED

  - TIME AND SET UP COMPLEXITIES REQUIRED TESTING FOR EACH ADVOCATE SEPARATELY

  - DIFFICULTIES ENCOUNTERED WITH TEST DATA COLLECTION AND TRANSMITTAL

    - TAPE RECORDER

    - CHANNELS OF DATA MISSING

  - ORDER OF DAMAGE INFLICTION BECOMES IMPORTANT

FIGURE 6

type of damage meaning that any permanent changes we made to that structure after we started, would require us to go back and repeat the baseline.

As a result, the order of the damage being inflicted became very important. We had a limited number of choices of what we could and could not do, and I would say that the overall criticism we faced at that point was that we were severely limited in the number of tests we could possibly conduct.

Figure 7 shows a list of the test scenarios from which we chose. There were two types of damage; i.e., major damage and minor damage. In the major damage tests, we could: (a) sever a brace on one face or diagonal, (b) cut two diagonals, (c) cut other members at the horizontal faces or near the base, (d) change the foundation conditions. The last change was one of the tests selected for our first test. In the minor damage, we could bend a diagonal, change the deck mass.

Early in the program, the deck became so well instrumented by all of the advocates in order to look for potential changes in the deck mass. We spent a considerable amount of time modeling the structure. We modeled it with a very detailed NASTRAN model and looked at the response of the accelerometer points with changes in deck mass. We felt any potential deck mass would easily be detected, so we eliminated that damage mode as one of the early tests we wanted to start out with.

In the future, we were interested in changing the deck mass or simulate marine growth, but these, we felt, were secondary to the primary objective of determining whether major damage could be detected by the NDE advocates.

We felt that a crack simulated in one or two horizontal members, was a more important test than all of the others. We then chose that failure mode as one of the second scenarios evaluated.

Figure 9 shows the cases we finally evaluated. We started out with the baseline tests of the undamaged tower and then proceeded to inflict two damage modes. The first test was to remove the shims and supporting bolts underneath one of the four corner legs of the tower.

The second damage test was to simulate cracking by partially saw cutting through two members in the lower bay. The third damage test completely removed the horizontal brace and the diagonals which tied the brace in place. That scenario was

Note: Text does not reference a Figure 8

POSSIBLE DAMAGE SCENARIOS

CONDITION	MAJOR DAMAGE
1	SEVERED DIAGONAL BRACE - ONE FACE
2	2 SEVERED DIAGONALS (ONE ON OPPOSITE FACES)
3	SEVERED HORIZONTAL AT BASE
4	2 SEVERED HORIZONTALS AT BASE (ON AN OPPOSITE FACE)
5	CHANGED FOUNDATION CONDITION
	MINOR DAMAGE
6	BENT DIAGONAL IN UPPER BAY
7	CHANGE IN DECK MASS
8	SIMULATED MARINE GROWTH
9	CRACK IN ONE OR TWO HORIZONTAL MEMBERS
10	PROGRESSIVE CRACKING OF HORIZONTAL AND DIAGONAL MEMBERS
11	INSTALLATION OF ONE OR TWO RISER PIPES

FIGURE 7

TEST SCENARIOS SELECTED

		Type of Damage
Test A	BASELINE - UNDAMAGED TOWER	NONE
Test 1	REMOVE BOLTS AND SHIM PLATES FROM ONE LEG ATTACHMENT TO DECK	#5 - Major
Test 2	PARTIAL SAW CUT THROUGH 2 MEMBERS (LEVEL 4 - FORCE B) AT JOINT	#9 - Minor
Test 3	REMOVAL OF HORIZONTAL AND "V" DIAGONALS ON SIDE B - LEVEL 4	#1 - Major
Test 4	PLAYBACK OF BASELINE TEST RECORDINGS TO ADVOCATES	NONE

FIGURE 9

we wouldn't give any telltale low frequency cantilever modes from partially cut parts or members whipping back and forth.

Test number two could be considered as minor damage; test three, as major damage; and test number one, as major damage. No test number four, as such, was run due to the extensive testing required to run the three above tests. The data that was taken as baseline data was disguised and given back to each advocate as an added test.

The test instrumentation used by the University of Maryland random decrement method was 17 accelerometers and three shaker positions. A total of 20 pieces of data were supplied.

The frequency response technique (Aerospace Corporation) had 34 accelerometers and two shaker positions, a total of 36.

A scoring procedure was initially proposed to evaluate how many pieces of data each advocate would require, how many instrumentation points each advocate would use and to weight this as a score item.

This was included in the report, but not considered to be of much merit, after we determined that both techniques could, indeed, locate damage to a certain extent with limited instruments, and could determine that damage did occur with varying amounts of instrumentation.

Figure 10 shows the results of the tests that we conducted.

In test number one, we unbolted one of the four bottom legs and both advocates could detect the failure and detect approximately where the failure occurred or the type of failure.

In Column B of Figure 10, we indicate a "confidence level", which is something that became quite controversial among our own group. This column was proposed by the ONR sponsor. Yet it has been pointed out by our engineers and others that if someone reports findings he is always confident about what he's proposing or at least would report so. In fact, if he is not confident about what he's reporting, he won't tell you. So if an advocate gives you an answer that he is 100 percent confident, at least he wants you to think he's 100 percent confident.

So column B became somewhat misleading. We decided that we would ignore the confidence level and only report it as a matter of inteerest.

SUMMARY OF DIAGNOSES SCORING

TEST NO.	DAMAGE TYPE *	U. OF MARYLAND, RANDOM DECREMENT				AEROSPACE CORP., FREQUENCY RESPONSE			
		A	B	C	D	A	B	C	D
1	MAJOR (5)	X	100%	X	O	X	100%	X	O
2	MINOR (9)	X	100%	X		X	50%	X	O
3	MAJOR (1)	X	100%	X		X	100%	X	X
4	NONE	X	100%	X	N/A	X	100%	X	N/A

* See Table 4.1

A - Identification of damage vs. no damage

B - Confidence in diagnosos

C - Severity of damage

D - Location of failure

X - Correct answer

O - Partially correct answer

FIGURE 10

Column C then became the most important item, severity of damage. Could an advocate detect such damage? Could he detect the severity of damage?

To reiterate some of these techniques are ideal for different purposes. We believe, for example, that the random decrement method is ideal for indicating the initiation of failure or early failure. In fact, that's one of it's primary claims.

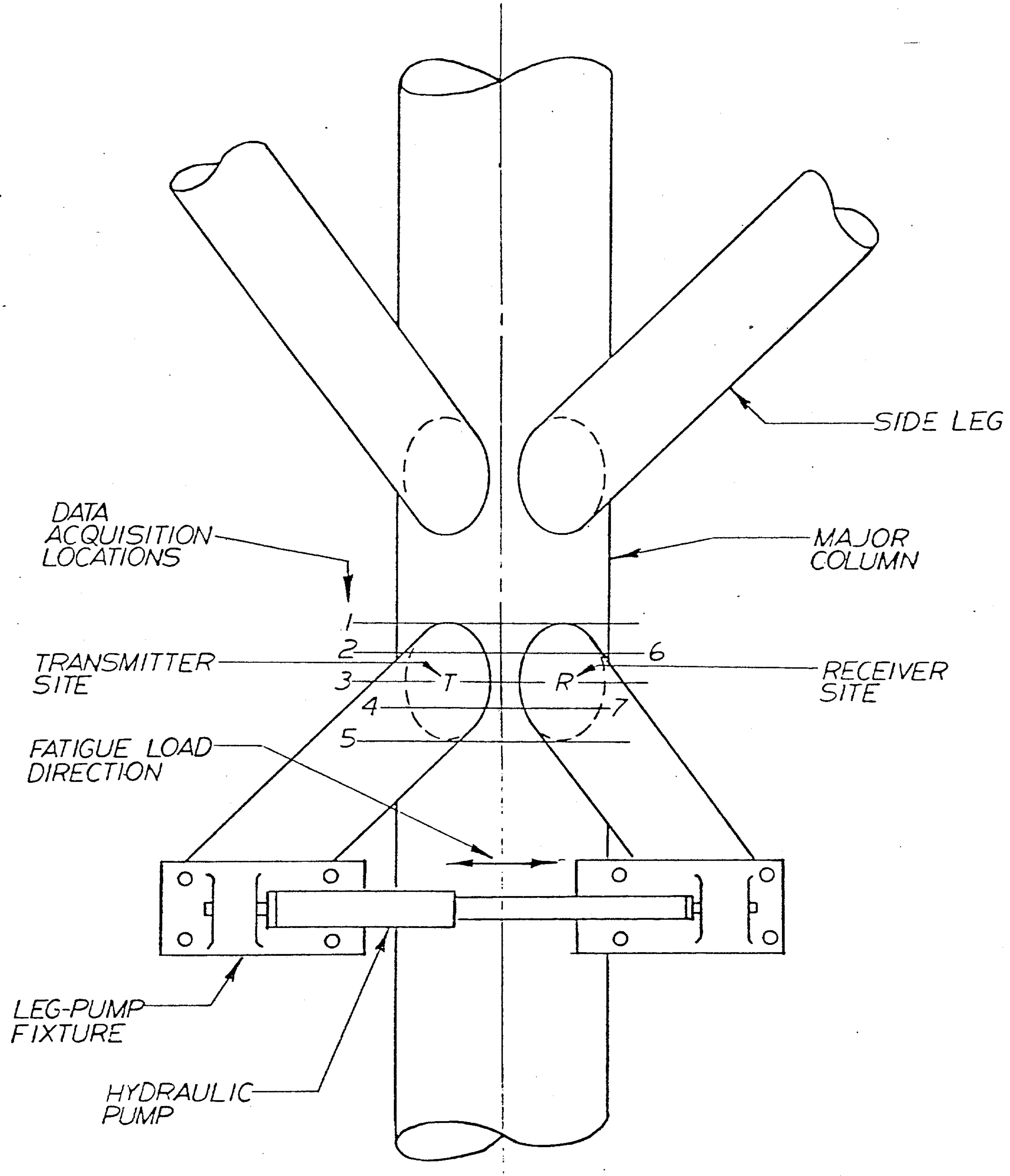
Alternately, the frequency monitoring technique is claimed to be ideal for locating damage, and also indicating the level of damage. So these two are, in their own realms, and are complementary.

In predicting damage, both random decrement and frequency monitoring advocates scored well in determining the damage level.

The frequency monitoring did better in terms of locating the damage. The random method did better in terms of indicating that minor damage had occured. The location of the damage, as proposed by the random dec method, was not clearly presented to us; i.e., the method used to locate damage did not show in its results. We did know that the random decrement had considerable experience on this type of structure, and perhaps that was used as part of their analysis input.

K-Joint Tests

The acoustics emission test, as mentioned, was dropped from testing. The ultrasonic testing of the K-joint was carried out by Drexel University. In that technique (Figure 11) one diver was placed on the structure and a series of receivers were placed at several points around the K-joint. The testing technique evolved about an understanding of what the joint was supposed to show, in terms of it's response at each one of the receivers. These response patterns were evaluated in terms of their power spectrum and density distributions (for each of those receivers). These were compared with the responses seen by the receivers in the actual fatigue test, and a mask was developed. To compare the two; i.e., the response that you would expect with the response from previous testing. That technique appeared to be successful. The details of this technique will be presented later by Dr. Rose.



ULTRASONICS INSTRUMENTATION

FIGURE 11

DR. PERRONE: You made a comment about the purpose of the Round Robin tests. From our viewpoint, testing one method against the other is good. Part of what we have done at ONR, in Research and Management, is to try to push the frontiers in one direction or another. When you've got an area where you reach a certain level of confidence, and you'd like to see how good are you in that area, you can do it with this kind of competitive test philosophy. We did it in shock problems, acoustic problems. And here was a problem in NDE.

The question was not one methodology pitted against another. It was how useful or how good is each of them? The answer, I think, initially was, they may all be very good; they may all be totally useless. They may all be good in part in different domains. Probably the last is what actually occurred. I think it was not so much a competitive thing, as much as an objective assessment. That's how I would characterize it.

DR. DAME: I think that's true. What I was trying to say was that in our evaluation of performances, we set up a scoring scheme, which may have been a disadvantage, because it's very difficult to score each one of these techniques competatively.

DR. PERRONE: On a question of the confidence level indication. The difficulty we anticipated was that we had only four or five test events. If you simply toss a coin, you should be able to get two or three of them right. So it statistically becomes questionable, and the notion of putting a percentage of confidence in there says it's right or wrong by putting a confidence level of 100 percent or 50 percent or something like that. You at least take away the statistical insignificance of it.

In a way I think it was useful that each of the people were called upon to say "I'm absolute sure" or "I'm not sure". This takes away from the simple guessing.

DR. DAME: That was our understanding so we went along with it. We also realized it was introduced because of the limited number of tests. Really what is required is more testing -- more cases.

DR. PERRONE: If we had the time and the money, we could have done more.

DR. DAME: It was brought to our attention that if an advocate puts something down, and he says he's confident about it, how can you really evaluate that? You just have to say that he's very confident, or that he is correct. From a statistical point it is difficult to conceive that a 100% confidence could be achieved in every test, yet Dr Yang was 100% confident on every test he reported.

And others were not as confident. I don't know how to evaluate that. That's how we arrived at the conclusion that the confidence level was something that was very hard to evaluate, because documentation supporting the confidence level was not there. It wasn't prepared as part of the requirement for response from the advocate. If we had spent more time telling them what the confidence level meant and what they had to give us to prove the confidence level, I think we would have been in a better position.

DR. PERRONE: In retrospect, I think it even played a useful role there. It's not a contest, but a learning experience. I think on balance, it achieved nicely.

DR. DAME: From our point of view, from the bottom line, both techniques in the blind mode can detect damage, can indeed detect whether major or minor damage has occured, and to a limited extent can locate damage and type of damage.

A major shortcoming of the program was that, because of the limited funds and the limited types of tests that were run, we could not perform simple things like simulating marine growth or evaluating damping,or investigating environmental considerations, test moving masses on the deck, place masses on members to indicate just how these NDE proedures would perform under those circumstances.

As a result, we have left open the question of whether these techniques can evaluate those types of damage situations.

NICK CARINO, (National Bureau of Standards): In your test set-up, was the platform freestanding, or is it under some kind of loading? Was it sitting in a laboratory?

DR. DAME: The test was conducted on a tower that was bolted down to a rigid platform with a series of four bolts at each leg point, except for the case where we removed one of those leg support points, left it free and had the other three legs bolted down.

The shakers were applied at discrete points in the tower structure. The shaker locations were dictated by the test advocates. They were not programmed to simulate environmental loading. They were programmed to simulate either white noise or some sort of power distribution that the advocates wanted. Environment testing is another phase of the program.

DR. YANG: (University of Maryland). I think there is one aspect which might be pointed out. When you mentioned that there were 34 accelerometers used by, I guess, Sheldon Rubin (Aerospace Corp.), and 17 used by random decrement, there might be a slight clarification on that.

One point is that of the 17 accelerometers, we only requested data of a few. I believe it was 4 to 6, and we did not touch any of the other data.

The reason for the extra accelerometers was that since they are going to do an extra test, we were going to use that later for some other purpose. In the meantime, we only asked for 4 to 6 accelerometer readings. So we got tape recordings of only 4 to 6 accelerometers, and we were analyzing that.

DR. DAME: One thing that I will point out is that there is a complete report that describes, in detail, your response and how many accelerometers you actually used for your analysis.

The availability of the information is there, in terms of what you asked for, your test points, and what you actually used. If you look at the final report, there is a score for each technique, and you will see just how well you did in certain respects and how well others did in the same or in other respects.

The number of instrumentation points is just a matter of what you requested for the test procedure.

Mr. H.S. LIU, (National Bureau of Standards): You mentioned earlier that there was a loss of transmission data shortly after testing began. But even though that happened, each group got the information they wanted, right?

DR. DAME: That is correct. One thing that happened with the random decrement test was that the investigator had reserve data channels. They could pick another data point actually, another accelerometer, and use that channel. Does that answer your question?

MR. LIU: Basically, both groups have an adequate number of data that they were originally shooting for.

DR. DAME: Unfortunately, the Aerospace Group lost a data point on a particular location that could have told them where damage had occurred. As a result, they didn't do as well in locating that damage point. They did not know exactly where the foundation leg was unbolted, but they did get the right mode. They did detect the type of damage.

With Jackon Yang's case, his group lost one channel during the baseline test. He then, asked the NASA Goddard test group to supply other data channels.

MR. LIU: What was the cause of loss?

DR. DAME: The channel that was lost was due to a dropout of the charge amplifier or filter after tests started.

PETE ALEA, (NASA Goddard): We were using all analog equipment to do the analysis that Jackson Yang required.

Inevitably, every once in a while there was an equipment failure that we didn't catch.

DR. YANG: To reinforce that and answer the question, it was rare. It only happened a couple of times. All of a sudden, as we analyzed these tape recording data, we noted the random dec was going all over the place.

Then we started looking a little more at the time response to see whether there might be some chopping of our signal. So we noticed this and asked for the original data.

DR. GREEN: As I understand it, various investigators told you and NASA what modes of excitation they wanted. Then NASA recorded everything. Is that right?

DR. DAME: No. Each advocate was asked to put together a test plan. Each test plan was collected and integrated into one overall test procedure. Then reviews were held with the advocates to negotiate this test plan.

I am sure they could not get everything they wanted on this one test.

DR. GREEN: Did they describe the frequency responses they wanted on the accelerometers?

DR. DAME: That is correct. Then NASA recorded all data, and in the case of the random decrement analysis technique and at the investigator's request they held back a lot of the data.

FREQUENCY MONITORING METHODS

Dr. Sheldon Rubin
The Aerospace Corporation

DR. RUBIN: I am Sheldon Rubin of the Aerospace Corporation, and our role in the Round Robin Test Program was to pursue a series of techniques under the general category of frequency response monitoring.

We actually investigated three distinct subsets of frequency response monitoring and as you will see in the detailed report, different instrumentation supported each of the three different techniques.

Dr. Dame actually discussed three techniques (see Round Robin Tests), but in fact we were evaluating three distinct techniques, each using different instrumentation.

I want to concentrate on one of the techniques which we call flexibility monitoring, because we feel that it has very strong application to the field requirements for this type of monitoring. So I will go into that in some detail and not get into the other two techniques except to identify them a little further along in the talk.

Figure 1 is an outline of what I propose to cover. I want to begin by describing what I mean by flexibility monitoring, how is it useful, what is its intended application, how it can be implemented in an actual field situation, what are the key aspects of this technique, the key requirements, and what has our experience been with this technique.

Our first experience was the Round Robin Program just described by Dr. Dame. I will describe some subsequent testing on that same Round Robin model to get data on additional changes that Dr. Dame spoke about.

Then we have conducted an experimental evaluation on two field tests in the Gulf of Mexico during the past year, and I will describe those very briefly.

Finally, what I see as the actions needed in the future to continue the development of this technique.

Figure 2 is an outline of flexibility monitoring (a subset of what frequency response monitoring techniques). It is basically a vibration-based technique specifically designed for a class of structures which are steel jacket fixed platforms used for oil and gas drilling and production.

OUTLINE

- WHAT IS FLEXIBILITY MONITORING?
- USEFULNESS
- IMPLEMENTATION
- KEY ASPECTS
- EXPERIENCE
- ACTIONS NEEDED

Figure 1

WHAT IS FLEXIBILITY MONITORING?

- UNIQUE VIBRATION TECHNIQUE AIMED AT JACKET STRUCTURES
    - DAMAGE DETECTION
    - SYSTEM IDENTIFICATION
- FOCUS IS ON INTERLEVEL AND FOUNDATION FLEXIBILITIES
- UTILIZES FUNDAMENTAL MODES

Figure 2

There are really two types of applications. The basic one is detection of underwater damage, either in the jacket itself or in the foundation of the structure.

But we also see that the technique is even more broadly applicable as a technique for system identification, more specifically, the stiffness distribution, if you will, of the structure and foundation, and can be useful quite apart from the damage detection viewpoint.

The focus of the technique is to subdivide the structure into its sections and to look at the stiffness properties of each individual section. This is why the technique is so powerful for locating damage and also for countering the fact that these structures are very highly redundant.

So we are getting away from a very global technique, looking at the overall properties of the structure, and trying to focus in on the local properties of sections of the structure.

Finally, what we are using in the field is just the ambient-induced vibration. We are not going to excite the structure artificially.

The question is the quality of the data that one gets under those conditions, and for reasons that we will go into, only the three fundamental beamlike modes of the structure are employed in the technique.

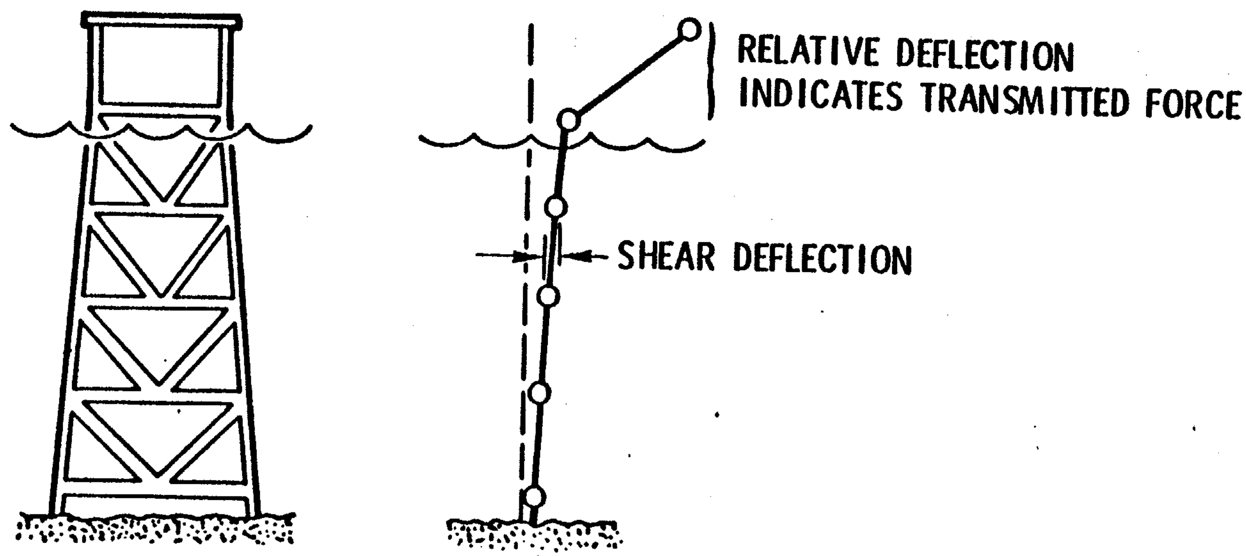
Figure 3 describes the basic concept of the approach. This is a schematic of a tower just like the one used in the Round Robin Test Program. If we imagine that this structure is a shear beam supported at the base and we look at the deflections of such a structure from its neutral position, we will get a deformation shape something like this, where the above-water portion, the water level, would typically be this position.

There was no water in the Round Robin Test, but in the field situation, sea level will be somewhere below this uppermost horizontal. The uppermost portion is typically much more flexible than the lower portions of the structure.

So under wave/wind loading, the structure will be deformed -- say a fundamental sway shape -- and will move off the neutral position.

FLEXIBILITY MONITORING:

DETERMINATION OF SHEAR FLEXIBILITIES



FLEXIBILITY = DEFLECTION/FORCE

Figure 3

The concept is that if we can identify the shear deflection across an individual bay, and if we consider the upper portion of the structure to be a huge strain gage, if you will, whereby the relative deflection between the deck, this uppermost section, and the next section down -- that relative deflection is an indication of the force being transmitted down the structure as a result, basically, of the inertial actions at the deck.

Then we can define a flexibility parameter for this idealized structure simply as a ratio of the shear deflection at a bay divided by this relative deflection, which is an indication of force.

So flexibility is deflection over force -- the usual kind of definition of flexibility. That is the overall concept.

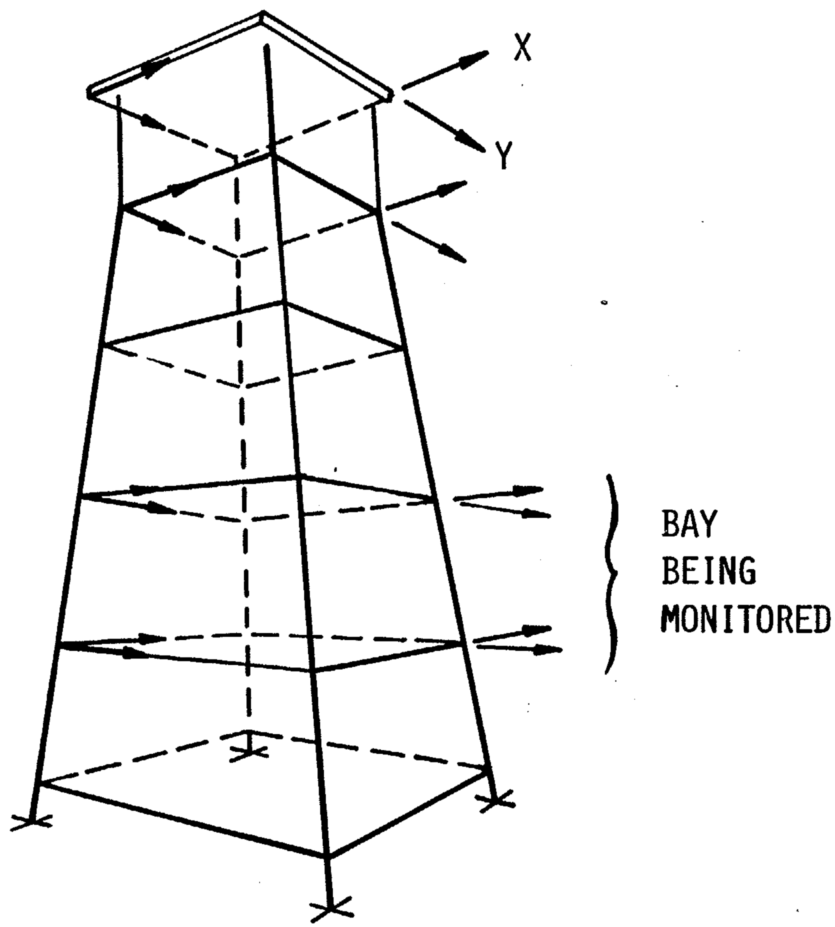
Figure 4 shows the way this was actually done on the Round Robin model and would be done on any structure of this sort is to place accelerometers at the various elevations, and specifically -- although doing a little bit beyond what was done in the Round Robin model because of the limitation of the number of accelerometers that could be utilized, and the fact that we were trying to evaluate three distinct techniques -- at each level; for example, the deck, four accelerometers, two at opposite corners in an X and a Y sequence.

In the Round Robin Test we actually had only three accelerometers at most of the levels. But let's talk about the general case -- four at the deck, four at this uppermost level just above the waterline, and suppose we are trying to monitor this bay; we would have four accelerometers at the upper edge of the bay and the lower edge of the bay. And what we would detect would be in the fundamental modes of a vibration, the relative amplitudes among these various accelerometers, and from those relative amplitudes, we would calculate flexibility parameters.

Let me just specifically identify a flexibility parameter for the X direction motion in this particular bay.

If we took the two accelerometers at the upper edge of the bay in the X direction and averaged their two motions, that would give an average deflection in the X direction at this position. And if we took a like average at the lower edge of the bay and differenced those two, that would be an average relative deflection across this bay in the X direction.

FLEXIBILITY MONITORING: POSITIONING OF ACCELEROMETERS



- BAY AND FOUNDATION FLEXIBILITY PARAMETERS
  - FOR X & Y SWAY AND TORSION
- ADDITIONAL FOUNDATION PARAMETERS FROM VERTICAL MOTIONS

Figure 4

So four accelerometers are involved, two being added and two being subtracted, and in like manner, the deflection of the uppermost section would be formed. Then the ratio of the relative deflection in the X direction is what we identified to be a flexibility parameter in that direction for this bay. So that is the way the data is collected.

As an example, Figure 5 is based on an analysis that we performed on the Round Robin structure. If we imagine in this structure that a particular brace fails -- by "failure" we mean completely cut through so that it has no tensile stiffness -- and we calculate the flexibility parameters as I just described for the four underwater bays and plot the percentage change in the flexibility parameter, we get these results.

Basically, in the bays that do not contain failure, there is a negligible change in the flexibility parameter. In the bay that contains the failure, there was a very large change in the flexibility parameter.

It is recognized that this is a relatively low redundancy structure compared to most large structures in the field, and a change here is very substantial, over a 100 percent change in that flexibility parameter.

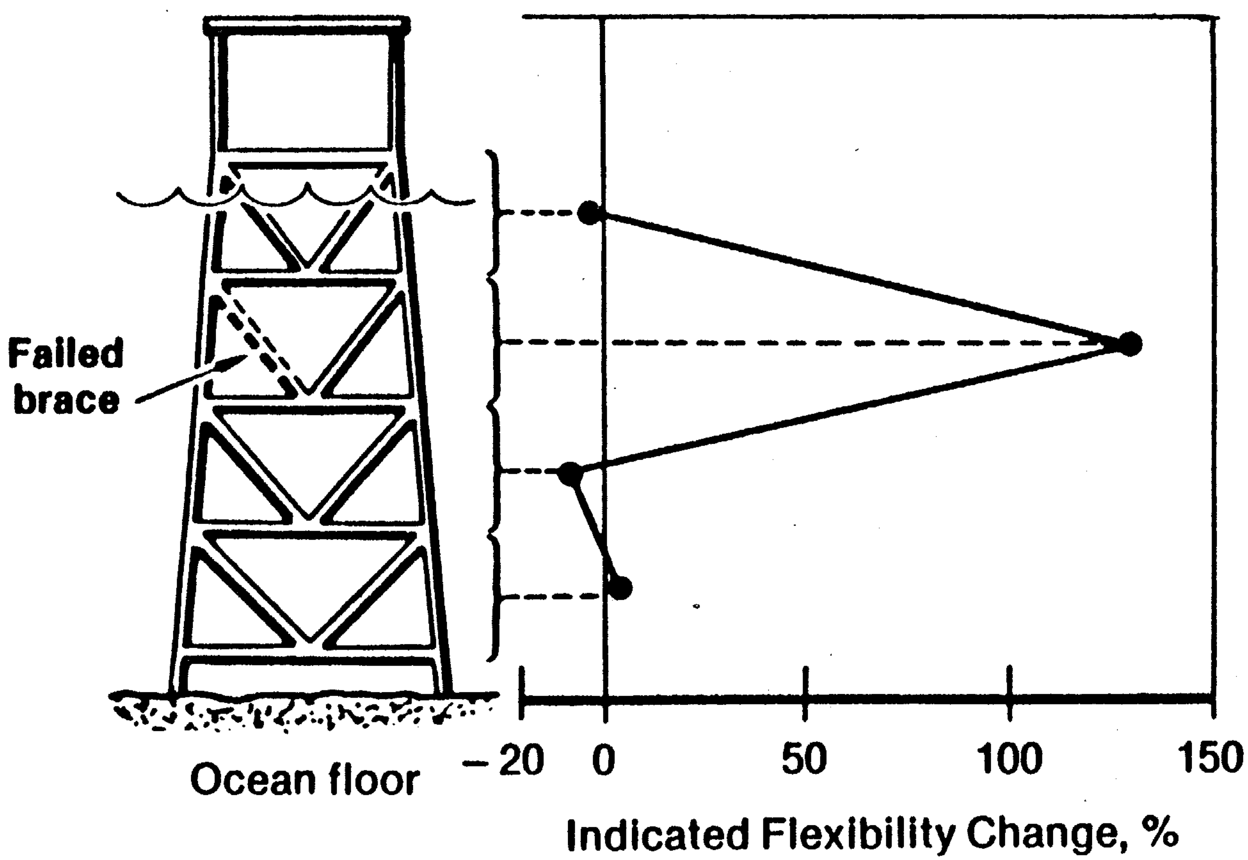
It is interesting however, that for this structure the frequency change in the fundamental mode caused by this very same failure, was only 1.3 percent. So from an overall frequency standpoint, it was a very modest change.

Figure 6 shows the usefulness of this sort of technique. We view this sort of technique -- where we're focusing on, really, the mode shape of structure and can look at the distributed stiffness properties -- as a technique for what we call conditioned system identification. Much work has been done in the area of system identification in which we have a test on a particular structure to see if we can improve the mathematical model as a result of the test experience.

And the focus of most of these techniques is on frequencies and shifting modes. To us, this will typically lead, particularly on a very redundant structure, to a poorly conditioned system identification problem. Consequently, the results will be uncertain and can be misleading.

We believe that this kind of technique will lead to much more conditioned results that one could have more confidence in, and results that will be much more sensitive to the

FLEXIBILITY MONITORING EXAMPLE



- FAILURE CAUSED 1.3% FREQUENCY REDUCTION

Figure 5

USEFULNESS

- MEANS FOR WELL-CONDITIONED SYSTEM IDENTIFICATION
  - LINEAR MATH MODEL EVALUATION/CORRECTION
  - STRUCTURAL HEALTH ASSESSMENT
- IMPLICATIONS
  - REFINE ASSESSMENT OF MONITORED STRUCTURE'S CAPABILITY
  - REDUCE UNCERTAINTIES IN FUTURE DESIGN ANALYSIS
  - REDUCE NEED FOR SAFETY INSPECTION INVOLVING UNDERWATER OPERATIONS
  - ENABLE RAPID HEALTH ASSESSMENT AFTER MAJOR EVENT

Figure 6

local parameters of the structure. So the possibility of just using this technique to evaluate mathematical models and to correct those models is there, but the original intent was for structural health assessment.

As we do more system identification and get a clearer picture of the way structures really behave in the field -- including the foundation, the mud contributing to the bottom support, which is a very uncertain area for design -- we ought to be able to improve our future design techniques.

The original idea of the technique, however, was for health assessment, and the idea was, can we provide an instrumentation technique which would be helpful, in addition to the diving type of inspections, or even vehicle type inspections, that might be conducted? Would this be a useful augmentation to the kinds of inspection and reduce the need for as many underwater inspections as are being carried out.

Another fact is that after some major event --such as a large storm or earthquake -- if one wants to get a rapid assessment of the health of the structure to go back into production, this technique would provide a capability for a rapid assessment without having to go into, for example, an underwater inspection program, which might be difficult to implement on a very short-term basis.

Figure 7 shows more about the implementation of the actual field test.

Basically, accelerometer packages would be deployed at the corners of the deck of the structure, and several structures have been outfitted with what we call chutes, which are basically square tubes that have been installed down corner legs of the structure in which an accelerometer package can be dropped from above water and locked into place at various underwater positions.

It is this approach that was used in the field testing. The idea was to detect the ambient fundamental vibrations, and we're talking of a level of vibration under relatively calm conditions of the order of 1 milli-G at the deck. These were the levels we're working with. That's the highest level in the stucture at the deck. It gets lower and lower as we go down, so we're in the general range of 1/10 to 1 milli-G in the levels of vibration.

Instrumentation that has the capability for detecting these quite well is available. The fundamental vibrations, lead

IMPLEMENTATION

- DEPLOY ACCELEROMETER PACKAGES
  - DECK CORNERS
  - DOWN CHUTES AT BOAT AND UNDERWATER LEVELS
- DETECT AMBIENT FUNDAMENTAL VIBRATIONS
  - HIGH SIGNAL/NOISE
  - PRECISE DYNAMIC CALIBRATIONS
- DETERMINE FLEXIBILITY PARAMETERS
- RELATE TO REFERENCE DATA
  - MATH MODEL PREDICTIONS
  - PREVIOUSLY MEASURED PARAMETERS

Figure 7

to high signal to noise ratios, so that rather accurate results can be obtained. This is absolutely essential to the success of the technique.

Also required are rather precise dynamic calibrations, and these also can be conducted. The calibration procedures are not the normal ones that are used for vibration testing.

The flexibility parameters are determined in the general way that I described, and then they can be related to two kinds of reference information. For example, predictions from the mathematical model. More precisely, if one does a baseline test and obtains the flexibility parameters in a baseline condition, then subsequent tests would provide a comparison of those parameters with the ones obtained in the baseline. And I will show some laboratory results of that kind of comparison.

Figure 8 is an example of spectra in a test we did some years ago for the concept of flexibility monitoring. In this test, we had an opportunity to measure the vibrations in both a calm and rough sea. This happens to be at a 12-foot level on the structure, the level just above sea level.

This is an acceleration spectrum. The acceleration value is in milli-G's squared per hertz. Whether we're dealing with a rough sea or calm sea, I'd like to point out that the fundamental modes, fundamental sway, and fundamental torsion stand out rather clearly in the data and are uncontaminated by operations of the structure which include rotating machines, etc., that induce higher frequency content mostly up in this region modes. Some of these arrows indicate higher modes which, after very detailed examinations, can be seen in the data.

The flexibility monitoring technique ignores all of this and focuses entirely on the fundamental modes -- the information that is of high quality.

MR. COLE: You mentioned earlier you were using three modes. I wonder what the third mode would be?

DR. RUBIN: This happens to be in one direction. The third mode is the swing in the other direction, which happens to be at essentially the same frequency. I might point out, on the three structures that we have been involved in field tests on, these three modes have been in the range of 1/4 hertz to 1 hertz at the high end. So if you would to call that a typical range for these frequencies.

CLARITY OF FUNDAMENTAL VIBRATIONS

Sample Acceleration Spectrum
12 ft LEVEL

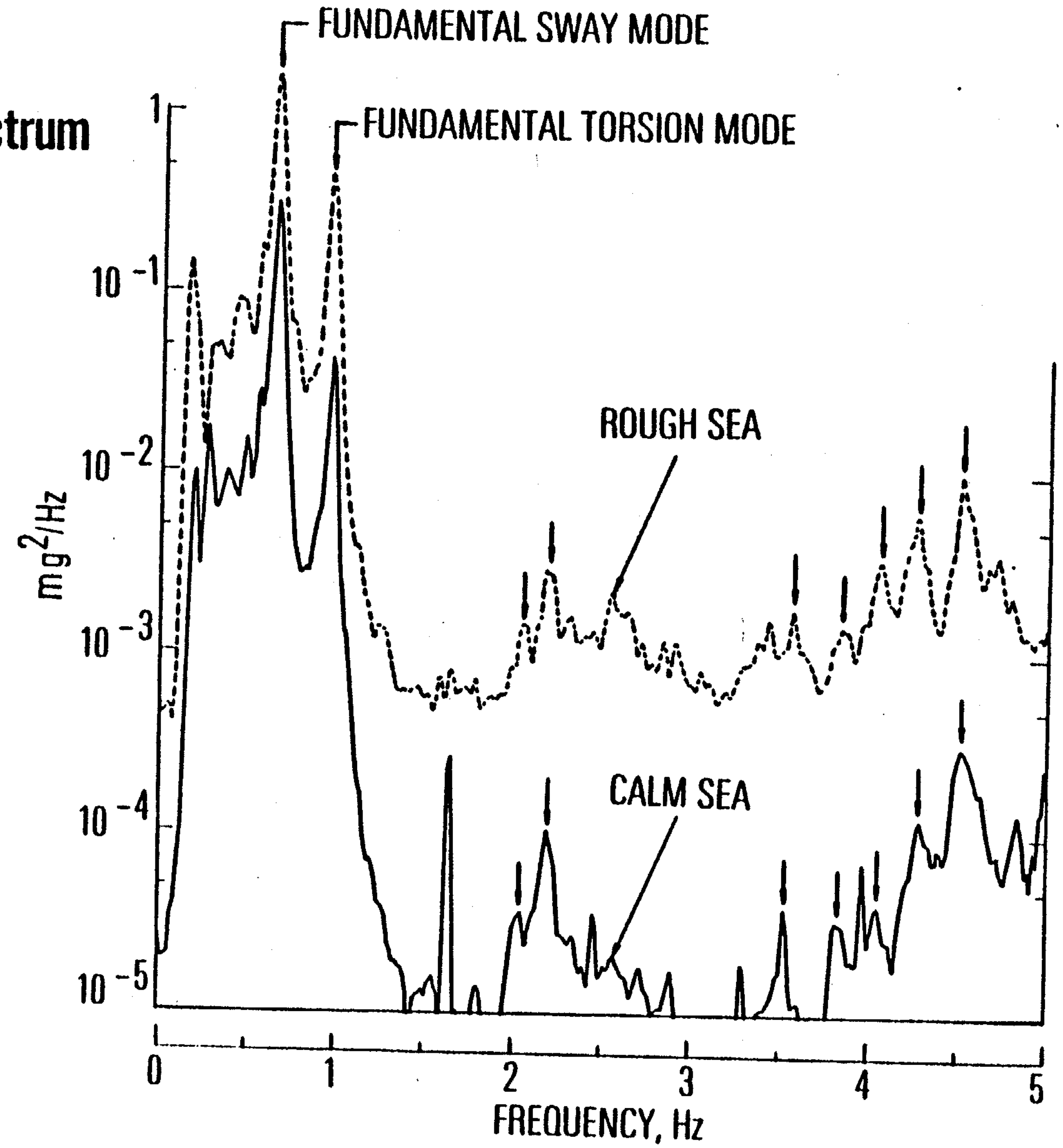


Figure 8

Figure 9 provides a reliable indication of strength loss; it gives a rather direct indication of the jacket or foundation flexibility change. I haven't discussed the fact that one can also get flexibility parameters for the foundation itself, in terms of shear stiffness, effective overall shear stiffness for the foundation, and also rotational stiffness. Parameters can be derived specifically for those.

It also very well discriminates mass changes. One of the things that happens operationally on a structure is that the mass on the deck is continually changing as the operation of the structure changes. That produces frequency changes, and one wants to be sure that one is not fooled by those kinds of changes in terms of detecting damage. This technique is a very strong discriminator of that effect, and you will see some results in a little bit here.

Also there is the matter of operational noise. Our last test was on a structure in a drilling phase, and we got some very good results, some degradation, but not a great deal.

So even in drilling, when it's a very, very noisy situation, we got rather good results with the technique. In normal operation, the results should be excellent on the basis of what we have seen so far.

The early vibration techniques involve detecting higher modes of operation, as well as the fundamental, and distinguishing these from machinery noise and from a number of nonlinear and secondary effects became very, very difficult. And there are studies which have pointed out those difficulties, including our own. In terms of how sensitive the technique will be, all we can do is give a preliminary estimate. There hasn't been enough field experience yet to give a precise definition of how sensitive the technique will be.

Part of this is due to the fact that the experimental work we've done so far has been with nonoptimum instrumentation systems. So far we have not done a test with an optimized system for this specific purpose. We have used what is available, what can be done with equipment already built and used in the best way we can, but not optimized. But my belief is that the technique will, when fully developed, be capable of identifying the failure of a single diagonal in a bay where perhaps no more than six diagonals are contributing in a particular direction. And that's a rather typical condition on structures. I believe we will get very confident indications of that level of damage with such a technique.

KEY ASPECTS FOR HEALTH ASSESSMENT

- RELIABLE INDICATION OF STRENGTH LOSS
  - DIRECT INDICATION OF JACKET/FOUNDATION FLEXIBILITY CHANGE
  - DISCRIMINATES MASS CHANGES
  - MINIMIZES OPERATIONAL NOISE CONCERNS
- SENSITIVE TO FLEXIBILITY CHANGE
  - REALISTIC GOAL: DETECT SINGLE DIAGONAL SEVERANCE IF ≤ 6 EFFECTIVE

Figure 9

This is Figure 10. Not only do we detect the bay in which a failure occurs, but also which of the faces of the bay the failure occurs on, because not only do we deal with the average pier deflections in the bay, but we look at happenings on one side versus the other side. Obviously, the side where the failure occurs will undergo larger deflections, and there'll be some induced rotations.

These are additional parameters I have yet to give a precise definition of but there is a very clear indication, as well, as to which face of the bay the damage is on.

As I mentioned, the technique should essentially be a low-cost technique, in the sense that the type of application that we had in mind is to be based on portable instrumentation brought to the structure on an as-needed basis, so that the accelerometer packages and the data acquisition system would not typically be resident on the structure to conduct the test over, perhaps, a several-day period, and then would be taken to another structure, and so on.

In that sense, the cost should be modest, relatively speaking. It does require that there be certain built-in provisions into the structure to permit packages of accelerometers to be deployed at the necessary underwater positions. The preparation of the structure, in advance, is a key factor in the technique.

Finally, the technique is essentially free of weather contraints. Anything that might influence, for example, diving operations, would not influence this kind of an instrumentation technique, whether the sea was calm or rough. As long as you could operate in any way in terms of deploying instruments, the technique should be useful.

Figure 11 is an outline of some aspects for system identification. This has been discussed previously.

Figure 12 outlines the Round Robin program and again, this has been discussed i.e., the way the program was run and what kinds of questions were asked basically, in each of these scenarios. Was damage present? With what confidence can you make that statement? How well can damage be located, and what is the degree of damage?

Figure 13 again, is a view of the model. I want to point out a few specific factors, I will be getting into, because after the Round Robin formal program was completed, we had

KEY ASPECTS FOR HEALTH ASSESSMENT (CONT.)

- FLEXIBILITY CHANGE LOCATABLE
  - JACKET BAY/FACE
  - FOUNDATION
- LOW COST
  - PORTABLE INSTRUMENTATION
  - BUILT-IN INSTALLATION PROVISIONS
- FREE OF WEATHER CONSTRAINTS

Figure 10

KEY ASPECTS FOR SYSTEM IDENTIFICATION

- COMPREHENSIVE EXPERIMENTAL DATA SET
  - FLEXIBILITY PARAMETERS
  - FUNDAMENTAL MODE FREQUENCIES
  - HIGHER MODE FREQUENCIES AND SHAPES AS AVAILABLE
- WELL CONDITIONED FLEXIBILITY IDENTIFICATION
  - FLEXIBILITY PARAMETERS STRONGLY CORRELATE WITH KEY MODEL FLEXIBILITIES
  - HIGH EXPERIMENTAL ACCURACY
- IMPROVED DATA SET ACHIEVABLE WITH CONTROLLED FORCING
  - EXPERIENCE NEEDED TO EVALUATE BENEFIT

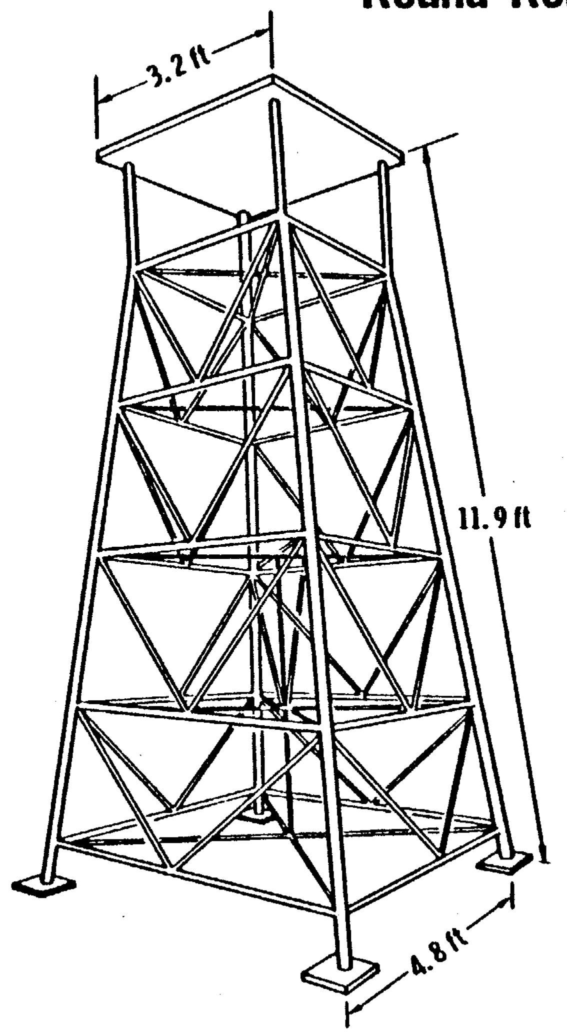
Figure 11

Round Robin Test Program
(USGS / ONR Joint Sponsors)

- OBJECTIVE
  - ASSESS PROMISE OF COMPETING NDE TECHNIQUES
- APPROACH
  - LAB TESTS OF SIMPLE SUBSCALE PLATFORM (NASA/GSFC)
  - BASELINE TEST BY EACH ADVOCATE
  - BLIND TESTS OF DAMAGE/CHANGE SCENARIOS
  - SUPPLY PRESPECIFIED DATA TO EACH ADVOCATE
  - ADVOCATES REPORT FINDINGS/RATIONALE
- REPORTING
  - DAMAGE PRESENT? CONFIDENCE?
  - LOCATION?
  - TYPE/DEGREE OF DAMAGE, RATIONALE, LIMITATIONS

Figure 12

Round Robin Test Model



- 1/14 SCALE
- NO PILES/CONDUCTORS
- NO WATER
- HARD FOUNDATION
- SHAKER EXCITED

Figure 13

an opportunity to do some follow-on testing to examine some other changes that were not possible during the Round Robin program. There were four base plates, one at the bottom of each of the corner legs, which were bolted down to a large concrete slab during the Round Robin test. One of the things that we wanted to do was make a type of foundation change where we introduced flexibility, something that might represent a more realistic foundation condition. And we introduced rubber pads, in effect, at the base of the structure. We floated the structure in rubber to create a flexible foundation.

Another thing we did was to place a rather large mass on the deck, off center, on one edge, to create a very substantial mass change and also cut a diagonal as a failure case. And I will be showing you the results of those tests.

Figure 14 shows the three distinct techniques examined.

Technique number one we call "global monitoring". For this particular specimen, it involved the fundamental modes, but more specifically, only the instrumentation that was above what would be the sea level, and the emphasis was on the frequencies of the fundamental modes of vibration and whatever mode shape information existed above the waterline. This is basically the kind of information that the original frequency monitoring techniques first introduced in an operational experimental sense.

The next was flexibility monitoring. Actually, the concept of flexibility monitoring came to mind when we were planning the things we could explore in this particular kind of program.

Our object was to learn as much as possible about techniques in general, given the factors involved in this particular program. And flexibility monitoring came out of our thinking about what can we possibly do in this program.

There was a third technique we called Remote Local monitoring. This is a technique wherein cracks in a member are detected with vibration instrumentation that is placed in individual members, perhaps by a diver, and the modes, the local modes are monitored. And there are several organizations in the North Sea area that are promoting this kind of technique.

MR. LIU: This is all under ambient conditions?

Round Robin Program (Cont'd)

- AEROSPACE APPROACH - EMPLOY AND REPORT 3 TECHNIQUES

  1. GLOBAL - FUNDAMENTAL MODES ONLY
  2. FLEXIBILITY - FUNDAMENTAL MODES ONLY
  3. REMOTE LOCAL - FUNDAMENTAL OUT/PLANE K-BRACE MODES

Figure 14

DR. RUBIN: Possibly ambient, possibly forceed motion. Both have been attempted. We thought about trying this local technique here. The contraints of the program were such that it really could not be implemented, because we would have to be able to interact with the test to be able to say on which member to place the accelerometers. That wasn't possible. There was to be an interaction.

So we attempted to do something quite more difficult. We attempted to identify partial failures, in members by shaking and measuring the vibration above the waterline only. That's what this technique represents. And what we were detecting were the fundamental, out-of-plane modes of these K-brace sections. But the only information used was from above-water instrumentation.

Figure 15 is just a summary of the four damage scenarios. The leg bottom release case was clearly identified by the global technique. There was no doubt other than which corner it was on, because some data was lost which would have indicated which corner. But one of two corners was identified with 100 percent confidence.

The second scenario was a halfway cut through one of the lowest horizontal members, and this was exactly the kind of failure where we would hope we would get it with this technique number three, and we did. But the change was so subtle that, if one had simulated marine growth on those structures, the change could have been as large. We didn't want to place 100 percent confidence on that kind of result, and that's why this statement of 50 percent confidence was given. However, by looking from a flexibility monitoring point at that structure, we could say with 100 percent confidence that whatever happened was minor. There was no significant change in the change of that structure.

In the case where a K-brace was severed, the fact that there was a diagonal failure, and the fact that it was in the lower portion of the structure could be identified with the global technique, but the flexibility monitoring technique identified the specific bay and the specific face with 100 percent confidence, and basically the degree of change that was observed corresponded to the prediction from the mathematical model very closely.

The final case was just a repeat of the baseline data. That was a throwaway for us. The results were identical, so there was no problem in discriminating that.

Round Robin Program (Cont'd)

- AEROSPACE RESULTS

DAMAGE SCENARIO	METHOD	FINDINGS
1. ONE LEG BOTTOM RELEASED	1	BOTTOM FAILURE OF THIS LEG OR OPPOSITE CORNER LEG (100% confidence)
2. HALF CUT THRU A LOWEST HORIZONTAL (2 places)	3	POSSIBLE HORIZONTAL FAILURE AT LOWEST LEVEL (50% conf); EXTENSIVE CRACKING IN A LOWEST K-BRACE ALSO POSSIBLE
	2	NO SIGNIFICANT OVERALL STRENGTH LOSS
3. REMOVAL OF A LOWEST K-BRACE	1	SEVERANCE OF ONE/BOTH DIAGONALS IN SINGLE BAY BELOW LEVEL 2 ON CORRECT FACE (100%, conf)
	2	ABOVE AT LOWEST K-BRACE (100%)
4. BASELINE	1	NO FAILURE (100% conf)

Figure 15

FOLLOWON TESTING ON ROUND ROBIN MODEL

CONFIGURATION COMPARISONS	% FREQUENCY CHANGES		
	X	Y	T
HARD → SOFT FOUNDATION	-9	-8	-1
INTACT → SEVERED DIAGONAL			
HARD FOUNDATION	-1	0	-1
SOFT FOUNDATION	-1	0	-1
ORIGINAL → ADDED DECK MASS (SOFT FOUNDATION)	-14	-15	-9

Figure 16

Figure 16 shows the results of follow-on testing. Now as I said, we had an opportunity to go back to this very same model -- it had been repaired, of course, after the damage -- and to do some things in the way of change. Regarding the soft foundation, the deck mass, on this table, I show several comparisons of configuration changes, what the changes were, what comparisons we could make, and what kind of frequency changes were associated with those particular changes. In the first case, we had the hard foundation, the model bolted down to the steady mass versus the soft foundation floating in a rubber case. In the two sway directions there were 8 or 9 percent reduction in frequency with the soft foundation, a 1 percent change in torsion. Another comparison was between the intact diagonal and the severed diagonal under both conditions -- the hard and the soft foundation condition.

In each case, the swaying in the direction that was affected and torsion frequency changed on the order of 1 percent with no change in the other sway direction.

The final comparison was between the original deck mass and this very substantial added deck mass off center. This was only done in the soft foundation case. We're talking about 14-15 percent reductions in the fundamental sway modes, 9 percent torsion. We essentially made something of the order of a 50 percent addition to the deck mass way off center.

So these were the changes. We wanted to experimentally identify the flexibility parameters, and we had two purposes in this program.

Number one, did the experimental results match the theoretical predictions?

Number two, this was viewed as a preliminary to field testing, and so we wanted to apply the type of data acquisition and reduction that we felt we would be able to perform on a field test and do it in a laboratory environment and compare those results against the formal laboratory data acquisition system.

This was possible at Goddard. They acquired the data with their normal laboratory system and processed the data as we prescribed, and independently we brought out portable analysis equipment that we would propose to use in a field test, independently evaluated the same parameters and made the comparisons. The result was that we got the same results, which provided a basis for using that particular system in the field tests I'll describe in a moment.

Figure 17 shows plotting some normalized mode shapes, and several cases are on here.

First of all, I have defined the levels. Level one is the first level below the deck going down to the bottommost level. This is the bottom of the structure. The vertical position is basically scaled to the level of the structure. The normalization is such that the average deck deflection is unity.

So, for example, in the baseline hard foundation case, is the average deflection mode shape at the various levels. The deck is one. Level one is roughly 1/10. When a diagonal was severed, the load shape distorted to the following deflection, and the flexibility parameter emphasizes the change in slope, if you will. And I think you can see where the failure which occurred between level 3 and 4 produced a dramatic change in slope of the sections.

We'll see those flexibility parameters in a moment.

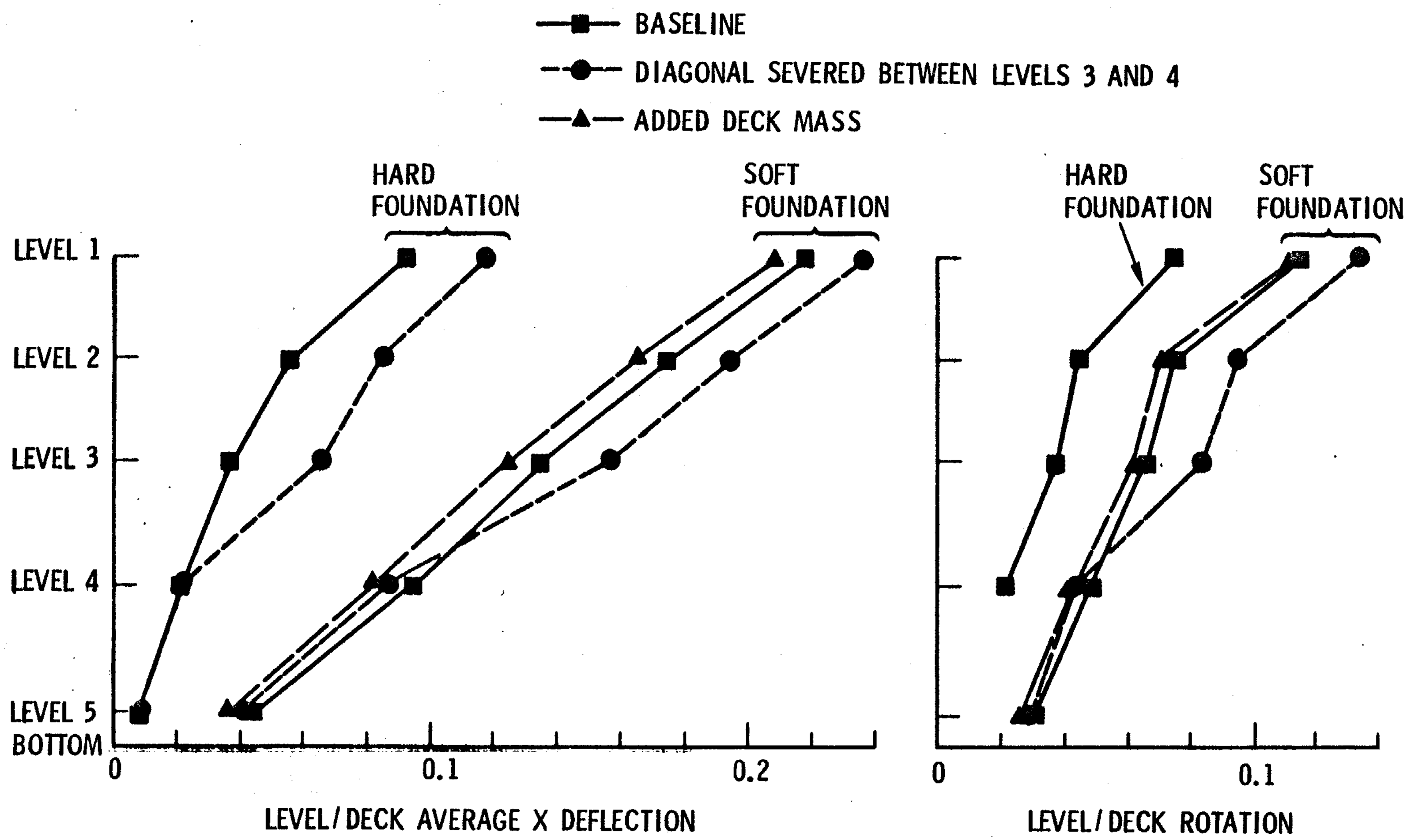
The soft foundation case with no added mass, no damage, shifted all the way over to here, a much larger base deflection and the whole shape leaned over.

With the failure in this portion of the structure, the shape changed like this; again, a significant slope change in the damaged bay. With the added deck mass, there was basically a uniform shift, a slight uniform shift to the left, but essentially no slope change.

And I show similar results here for torsion, but I won't go into them. That's the sway situation.

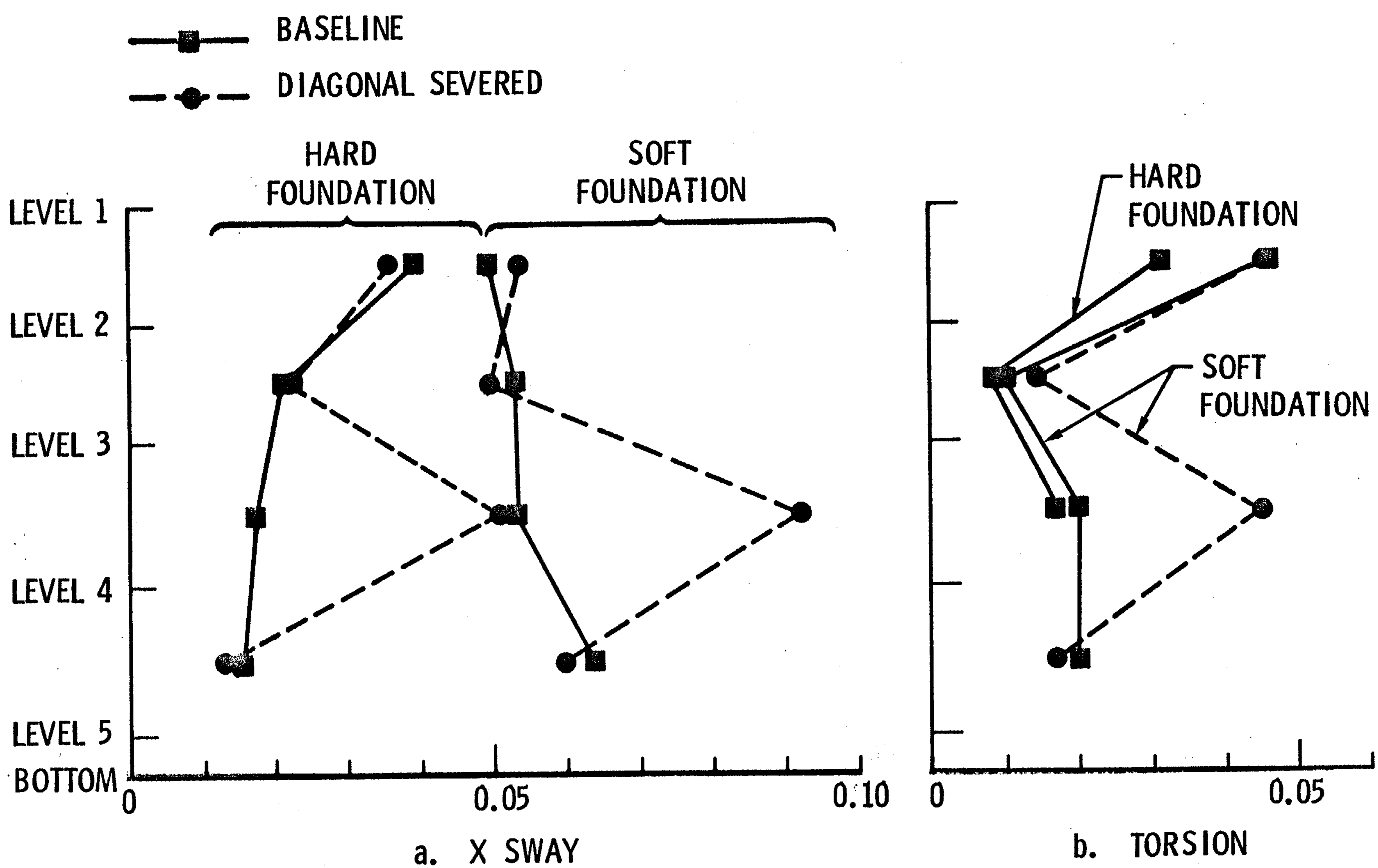
Figure 18 shows the experimental data. These are the flexibility parameters that were extracted for the X sway and torsion. The flexibility parameters for the various bays, the points are basically plotted in between the levels. So at this point they represent the flexibility parameters for the bay between levels one and two, two and three, and so forth.

In the baseline case, we have the square symbols. Those are the flexibility parameters. With the diagonal cut, the flexibility parameters exhibit this kind of change, and you see the only significant change is at the bay where the failure occurred.



Normalized Mode Shapes for X Sway and Torsion Modes

Figure 17



Flexibility Parameters

Figure 18

With the soft foundation, the flexibility parameters are shown here. There is a general shift in a fairly uniform fashion. But with the diagonal failure, the flexibility parameter looks like this. Again, the only dramatic change is at the bay, with the failure.

On Figure 19, a rather significant plot is the difference in the before and after flexibility parameters. Whether we start with a hard or soft foundation, we look for the change brought about by the diagonal cut. We basically get this curve, and these little horizontal bars represent the extremes of what happened, whether it was a hard or soft foundation.

So the change in the flexibility parameters is essentially independent of the foundation conditions. The change from a soft to a hard foundation, and nothing else, was just a general shifting. There are similar results for torsion.

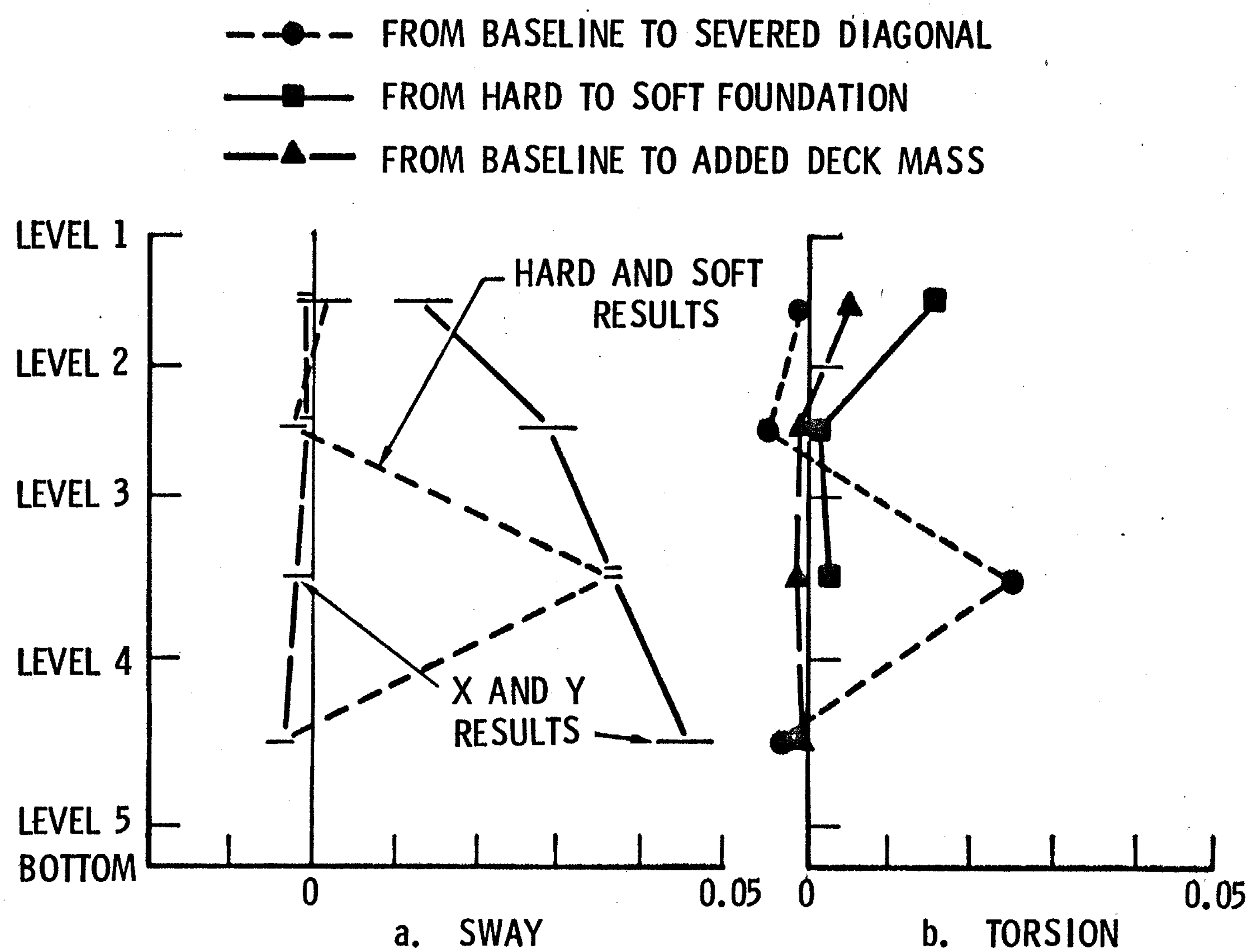
Figure 20 illustrates two field experiments, conducted in cooperation with industry. The first test was with the Shell Oil Company on their Cognac platform in April of last year. The platform has just gone into a production mode. The second test was conducted last month on Chevron's Garden Banks structure, which is still in a drilling phase.

In each case, chutes had been installed on the structures. On Cognac, these chutes only went about a quarter of the way down toward the foundation. So only the very uppermost portion of the structure was available on Cognac; however, on Garden Banks, the chutes went all the way down to the top of the skirt piles, not all the way down to the mud line, but practically all the way, as far down as one would like to go.

The instrumentation available was developed by the respective oil companies, primarily for design verification studies, and for the most part, they were quite suitable in terms of frequency response and sensitivity.

The class of instrumentation is called servo rebalance accelerometers -- sometimes, forces balance accelerometers -- which we believe is the ideal kind of instrument for this purpose.

Those are the kinds of accelerometers that have been developed by the oil companies. The special processing of the data and the real time evaluation was done by me during tests.



Difference in Flexibility Parameters

Figure 19

TWO COOPERATIVE FIELD EXPERIMENTS (GULF OF MEXICO)

- SHELL'S COGNAC (PRODUCTION MODE) - APR '82
  CHEVRON'S GARDEN BANKS (DRILLING MODE) - DEC '82

- TEST CONDUCT
  - CORNER CHUTES (1/4 DEPTH ON COGNAC: FULL DEPTH ON GB)
  - INSTRUMENTATION DEVELOPED BY OIL COMPANY
  - SPECIAL PROCESSING AND REAL-TIME EVALUATION BY AEROSPACE

- COHERENCE OBSERVATIONS
  $\geq$ 0.998 ON COGNAC & ON GB WHEN NOT DRILLING
  OFTEN $\geq$ 0.99 WITH DRILLING (CAN DETERIORATE FOR EXTRA NOISY OPERATION)
  DOES NOT DETERIORATE WITH DEPTH

- PRELIMINARY JUDGEMENT: CAN RELIABLY MEASURE FLEXIBILITY PARAMETERS WITHIN 10% OR BETTER
  - CAN DETECT SINGLE DIAGONAL SEVERANCE (IF CONTRIBUTES AT LEAST 1/6 OF OVERALL BAY SHEAR STIFFNESS)

- EXTREMELY VALUABLE LEARNING EXPERIENCES

Figure 20

Just to give you an idea of the data quality, I am going to talk about coherence, which is a parameter that comes from transfer function measurements and gives an idea of the quality of a transfer function. It is one of the strong measures of random errors and transfer function measurements. A value of one is perfect.

On Cognac and on Garden Banks, when we had a period during which there was no drilling, the coherence between accelerometers exceeded .998, which is extremely high, rarely gotten in laboratory situations. Even with drilling, most times on Garden Banks, we exceeded .99, which is still rather good. There were only certain times when the operation was particularly noisy -- when there was a lot of banging going on -- that coherence deteriorated from that somewhat.

A very important key result from Garden Banks, is that as you go down on the structure, the vibration levels get smaller and smaller and smaller. The question is, is the signal quality of the very bottommost portion of the structure adequate for this kind of required accuracy?

The answer out of Garden Banks is, yes. The quality of the signals did not deteriorate, and we actually went down to the very lowest bay on the structure; Dirceu Bolelho back here worked very closely with me and watched over my shoulder during all of this. He is with Chevron.

He can also be asked about the specifics of that particular experiment.

To me, this was a very key result, just obtained last month.

As I said, at this point, it's a preliminary judgement. We still do not have an optimized system, but my extrapolation of what we've been able to achieve, and what I think would be needed to optimize the system for this purpose, is that we ought to be able to reliably measure these flexibility parameters within about 10 percent and perhaps better. We ought to be able to detect a single diagonal failure. As I indicated before, these two tests have been extremely valuable learning experiences, and to my way of thinking, have completed a phase of the investigation of this technique.

(Picture not available)

Let me just show a picture. This is just a shot. This happened to be an instrumentation package containing accelerometers that are being introduced into the entrance of a chute and will be lowered by cable and locked into place. But that's the kind of an instrumentation package on one of these tests that we're talking about.

Figure 21 is my final chart. What do we need to do to continue the development of this technique?

I see four things. First, I believe there needs to be established what I am calling a reference chute configuration. It has to do with sizing of the chute, placement of the chute and angular alignment of the chute, and so on. Also, provisions for calibration, which I would like to see established, so there can be some commonality of development of instrumentation.

I am going to attempt to produce an outline for this in the coming few months. I would like to see chutes planned on new structures which conform to some reference configuration. It's very important that chutes be decided on and introduced at the beginning of the design. When they have to be added on after the structure has already been designed and largely fabricated, the costs get very, very high. But if one makes a decision at the beginning, the cost of adding the chute is quite modest.

Then, we have not yet used optimized instrumentation. I believe that an instrumentation system tailored specifically for this purpose should be developed, and that a formal demonstration program in that field be conducted wherein there would be visits to several structures, several times, to show repeatability. There would be some kind of a test structure in which failures and changes could be made in an ocean environment to confirm that the kinds of things done in the laboratory could also be done in the field, and to also do some system identification investigations with the technique.

DR. GREEN: Can you comment just briefly on that chute business. How did the instrumentation package get locked into the bottom?

DR. RUBIN: It's basically a square pipe, installed during construction, that is attached to a leg. The package is lowered, as shown, and through some mechanism, a latching is effected at the desired depth. So you measure the depth position down in the chute.

DR. GREEN: It's just stopped at some position in the pipe?

ACTIONS NEEDED TO PROMOTE FLEXIBILITY MONITORING

- ESTABLISH A REFERENCE CHUTE CONFIGURATION
- PLAN CHUTES ON NEW STRUCTURES
- DEVELOP TAILORED INSTRUMENTATION/ACQUISITION SYSTEM
- CONDUCT FIELD DEMONSTRATION PROGRAM

    SEVERAL STRUCTURES/REPEAT VISITS
    BLIND FAILURE/CHANGE TESTS
    SYSTEM IDENTIFICATION

Figure 21

DR. RUBIN: It's stopped in the pipe, but then it's locked in place.

DR. GREEN: Is there water in the pipe?

DR. RUBIN: In two cases, there has been no water, but the water could be there. It is just a question of the tightness of the seal. They're forced hard up against the pipe, in one case pneumatically and one case by an electric motor-actuated cam.

There are several possibilities that exist, so there is a solid connection.

MR. LIU: One quick question. Were you able to make a comparison between your experimental results and the theoretical results?

DR. RUBIN: We have not on these large field tests.

MR. LIU: No, I am talking about the Round Robin tests.

DR. RUBIN: Yes.

MR. LIU: You didn't show any results?

DR. RUBIN: I didn't show any results here. I think I mentioned to you that the change we saw in the Round Robin Program very much corresponds to what we had predicted. We're going to publish some of those results. There will be a paper coming up at the Offshore Technology Conference, and we'll cover some more of those.

MR. LIU: Were there any attempts made to measure actual lateral displacements versus your integration techniques to compare the chute information to that?

DR. RUBIN: Everything we did is from accelerometers. There were no independent deflection measurements to compare. We do not integrate or anything like that. At individual frequencies, ratios of accelerations are the same as ratios of deflections, so we deal with nothing but accelerations.

DR. PERRONE: Do you think you're getting close to an actual operational capability?

DR. RUBIN: This is the next step. These are the things that are necessary. It is a question of industry becoming sufficiently interested to become involved in this kind of an effort. That's where the ball really is at this point and this is what needs to be done.

DR. BASDEKAS: The way I understand it, what you were doing, for all practical purposes, is a very great reduction of experimental data to pinpoint the bay where the failure took place. By having sufficient instrumentation at the top and the bottom of each bay and having accelerometers at the four corners up and down, you end up having an accelerometer at every vertical and every diagonal in a face.

DR. RUBIN: At each level, that's right.

DR. BASDEKAS: You are reducing your global failure program to a local mode, because you have two accelerometers at the ends of each member.

DR. RUBIN: No, we do not have, at the end of each member, not at all.

DR. BASDEKAS: If you have a square, and the vertical members are at the top of each member, and at the bottom you have one accelerometer, also every diagonal ends up with the same --

DR. RUBIN: Well, what you had here was a four-legged structure, a very simplified case. In general, the structures are much more complicated. We only deal with outside corners, and there may be eight legs, and we're not at the end of every diagonal, by any means, even in this case.

DR. BASDEKAS: If you have eight legs, then you might have a set of eight, at each level?

DR. RUBIN: No, same number. The number does not change. The numbers I mentioned were equally valid. On the Cognac structure, the upper portion, an eight-legged structure, there was no increase with the complexity of the structure.

DR. BASDEKAS: Would it be possible to extend your method only above the water and nothing below it so you can address then the black box problem?

DR. RUBIN: That is the original approach, and that does not do the job that's really necessary.

DR. BASDEKAS: Was it attempted and failed?

DR. RUBIN: Many times.

DR. BASDEKAS: What was the reason for the failure?

DR. RUBIN: There isn't sufficient information that comes out of above-water instrumentation to properly discriminate the various mass changes that could occur, discriminate some of the non-linear effects that affect the higher modes which are essential to that technique. And equipment operational matters that confuse the picture.

That was the approach attempted. The flexibility monitoring requires that you go below water once you have the chutes in place, and all you're doing is taking these and just moving them down level-by-level, and taking the data, so we're not talking about enormous amounts of instrumentation; it's a sequence of tests.

It is a next order of complexity in an application, I agree, but I think there's an enormous increase in the sensitivity and the discrimination capability that is achieved.

DR. BASDEKAS: When you measure non-linearity, has that been observed in the higher modes only, or also the lower modes?

DR. RUBIN: Primarily the higher modes. There was an industry-sponsored report, the so-called Keith Fibush study in which they examined, theoretically, certain of the non-linearities that do occur on these structures, and the fact that they do have a significant influence on the higher modes. The higher modes are involved in that basic process and -

DR. BASDEKAS: Do you have any thoughts for only the lower frequencies in a black box input/output mode?

DR. RUBIN: This has been done; it's been published.

MR. DYRHKUPP: You mentioned that the oil companies had installed these chutes as a design verification. I presume that was to verify the dynamic analysis results that they based the design on. Is that correct?

You may want to use predictive models in the future. For instance, if damage resulted in a particular number down below, you could watch the model ahead of time and see what kind of response you would expect when you dropped your accelerometers down. I was just wondering if the results you obtained from taking these baseline measurements verify what you had assumed, what you had derived from your computer analysis.

DR. RUBIN: Well, first of all, the tests I'm talking about were strictly flexibility experiments. There was no formal system identification effort involved; secondly, they weren't even full baseline tests. On Cognac, the chutes were only available in the upper portion of the structure; and there were some other limitations. On Garden Banks; there just wasn't enough time to do the entire structure, so we selected regions, the uppermost portion, and then the very lowermost portion is where we did the most detailed work.

So they were not full baseline tests. As far as the industry's design verification studies, that's completely independent of anything I'm talking about. There's been no interaction between the two at this point.

FLEXIBILITY MONITORING

Dr. Shyam Sunder
M.I.T.

Figure 1 presents Research Topics in Flexibility Monitoring.

DR. SUNDER: My work has primarily been based on some of the research that my students have done at MIT for about six months or a year. In particular, NDE has been something we've only looked at since August, so I don't claim to be an expert in any of these areas. I would like to stress here that I've taken the devil's advocate standpoint in this particular area.

The issue that we want to really look at is the theoretical basis of the flexibility monitoring concept. As a concept, Dr. Rubin has well identified what it is, but how does it in fact relate to the lateral flexibility of an offshore platform?

I would also like to study the influence of multiple member severances on damage predictions. What happens if you have x - y strata on a certain level and an x - y strata on the second level as well. Is there an interaction?

Finally, I would like to present the sensitivity of the modal flexibility parameter to uncertainties in modal identification - issues I think which Dr. Rubin has already addressed and probably an area which is of significant concern if the concept of flexibility monitoring is really going to work.

I would spend a substantial amount of my presentation in talking about possible future research areas.

One issue that we need to look at is the modeling of error. We have talked about confidence bounds. Confidence bounds are important. However, clearly from a statistical standpoint, you cannot have 100 percent confidence in every prediction.

The second issue under possible future topics is modal identification methods, their accuracy, their efficiency, and their ability to be used in a systematic manner. Finally, I think an area that seems probably far-flung to me and also to many of you is the development of a computer-based damage assessment system using

RESEARCH TOPICS IN FLEXIBILITY MONITORING

THEORETICAL BASIS FOR FLEXIBILITY MONITORING CONCEPT

INFLUENCE OF MULTIPLE MEMBER SEVERANCES ON DAMAGE PREDICTIONS

SENSITIVITY OF MODAL FLEXIBILITY PARAMETER TO UNCERTAINTIES IN MODAL IDENTIFICATION

<u>POSSIBLE RESEARCH TOPICS:</u>

ACCURATE ERROR MODELLING TO ESTIMATE SENSITIVITY OF MODAL FLEXIBILITY PARAMETER

MODAL IDENTIFICATION METHODS: ACCURACY, EFFICIENCY, AND SYSTEMATIZATION

COMPUTER-BASED DAMAGE ASSESSMENT SYSTEM: KNOWLEDGE-BASED EXPERT SYSTEMS THEORY OF ARTIFICIAL INTELLIGENCE

Figure 1

knowledge-based expert systems theory of artificial intelligence. We'll get to the specifics as we go along. Figure 2 is a viewgraph essentially bringing up to speed - I think flexibility monitoring was first proposed by Rubin and Coppolino in the report that they published in 1981, possibly earlier. The method rests on the sheer beam behavior of a fixed offshore platform. The key assumption there is that the fundamental mode shape closely approximates the static deflections caused by a load at deck level.

What we need to stress is the fact that only the fundamental mode shapes are needed, so it avoids the problems of higher mode identification, and the method has low sensitivity to mass changes, particularly deck mass changes.

Figure 3 illustrates the Lumped Mass System and the Fundamental Mode Shape.

In order to simplify and probably relate to the issues in terms of specific results, I will be referring to a simplified offshore platform model which is a lumped mass model consisting of a series of masses and perceived flexibility associated with each level. F-1, F-2, F-3 and F-4 are flexibility coefficients, the true structural flexibility 1/K, one over the lateral stiffness for that particular bay. That's what I have called lateral flexibility.

In terms of the mode shape, the fundamental mode shape of that platform is represented in terms of x's, the mode-shaped value at a certain bay would be an x for that particular level and a modal flexibility parameter that I will define will be based on all the x's. So there's the modal flexibility parameter and there's the lateral flexibility of the structure, which is the true flexibility of the structure.

Figure 4 defines modal flexibility as the difference in the mode-shape values of the particular level, the upper part of the level minus the lower part of the level divided by the difference of the modal values of the top bay.

I guess the reason you use the top bay other than normalization is that it's usually above water, it usually doesn't have damage, and it also helps in flushing out the effect of deck mass changes.

Figure 5 shows that the initial objectives of some of the work we have done is to verify this relationship between

WHAT IS FLEXIBILITY MONITORING?

FLEXIBILITY MONITORING WAS FIRST PROPOSED BY RUBIN AND COPPOLINO (1981).

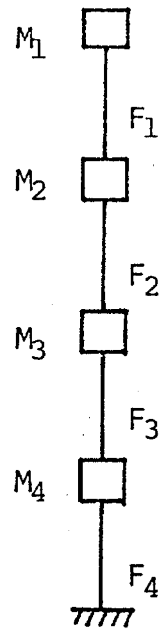
METHOD RESTS ON:

1. SHEAR BEAM BEHAVIOR OF A FIXED OFFSHORE PLATFORM.
2. FUNDAMENTAL MODE SHAPE CLOSELY APPROXIMATES THE STATIC DEFLECTIONS CAUSED BY A LOAD AT DECK LEVEL.

ADVANTAGES:

1. ONLY THE FUNDAMENTAL MODE SHAPE NEEDED. AVOID PROBLEMS OF HIGHER MODE IDENTIFICATION.
2. LOW SENSITIVITY TO MASS CHANGES.

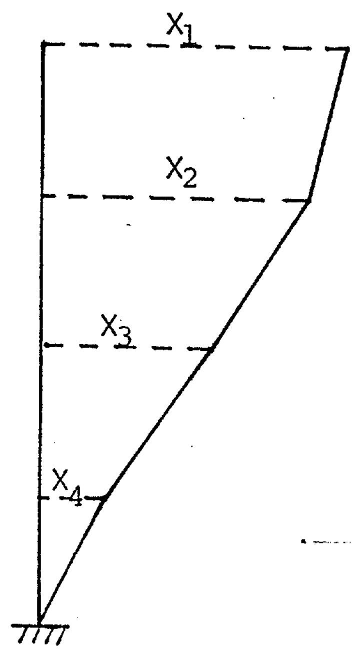
Figure 2



M - MASS

F - FLEXIBILITY

LUMPED MASS SYSTEM



FUNDAMENTAL MODE SHAPE

Figure 3

DEFINITION OF MODAL FLEXIBILITY

MODAL FLEXIBILITY IS DEFINED RELATIVE TO THE TOP BAY:

$$S_i = \frac{X_i - X_{i+1}}{X_1 - X_2}$$

i REFERS TO THE BAY CONCERN

Figure 4

OBJECTIVES

1. VERIFY THE RELATIONSHIP BETWEEN MODAL FLEXIBILITY AND LATERAL FLEXIBILITY

2. INVESTIGATE MODAL FLEXIBILITY FOR MULTIPLE MEMBERS FAILURE

3. EVALUATE THE SENSITIVITY OF THE MODAL FLEXIBILITY ESTIMATES TO INACCURACIES IN THE FUNDAMENTAL MODE SHAPE ESTIMATION

Figure 5

modal flexibility and lateral flexibility to investigate the modal flexibility changes for multiple member failure; finally, to evaluate the sensitivity of the modal flexibility estimates to inaccuracies in the fundamental mode shape.

Figure 6 illustrates that if you plot, for example, the change in the fundamental period, this is now a two-degree of freedom system that I'm talking about for which you have an analytical solution for the fundamental frequencies and the mode shapes.

If you plot the change in fundamental period with the lateral flexibility, you find that the lateral flexibility of the structure is a lot more sensitive to a particular damage, to a particular change in the stiffness of a particular bay. On the other hand, the fundamental period changes are very small.

If you do the same, if you plot the percentage change in modal flexibility, modal flexibility deriving from the mode-shaped values against the lateral flexibility or the true flexibility of that structure, you find that there's a fairly good correlation between those two parameters. It's a linear function, it's not a one-to-one correspondence - when you have a 100 percent change in modal flexibility if there'd been a one-to-one correspondence.

The thing to keep in mind is that there is not a one-to-one correspondence between the change and lateral flexibility and the change in modal flexibility.

Figure 7 is the result I obtained by assuming this 2-degree of freedom system, a mass M 1 and a mass M 2, a stiffness or flexibility F 1 and a stiffness or flexibility F 2.

I can carry out that analysis and generalize it by defining a mass ratio or M1/M2. This is again a 2-degree of freedom system and a flexibility ratio F 2 over F 1. And on the y axis I plot S 2, which is the modal flexibility of the bottom bay of this 2-degree of freedom system.

If I plot the S 2 versus B, I find that there is a significant correlation, but I think the important thing we see here is that there is some dependence on the mass ratio.

If you look at a mass ratio of 10, you essentially have a 1-degree of freedom system. For that particular system there's a one-to-one correspondence between the modal flexibility and the lateral flexibility.

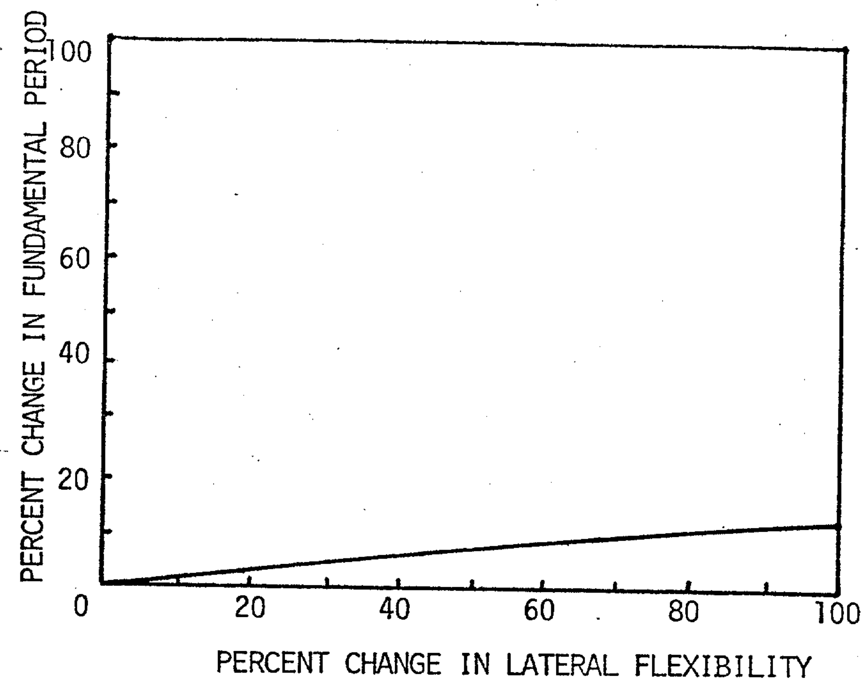


FIGURE 1 CHANGES IN FUNDAMENTAL PERIOD vs CHANGES IN LATERAL FLEXIBILITY

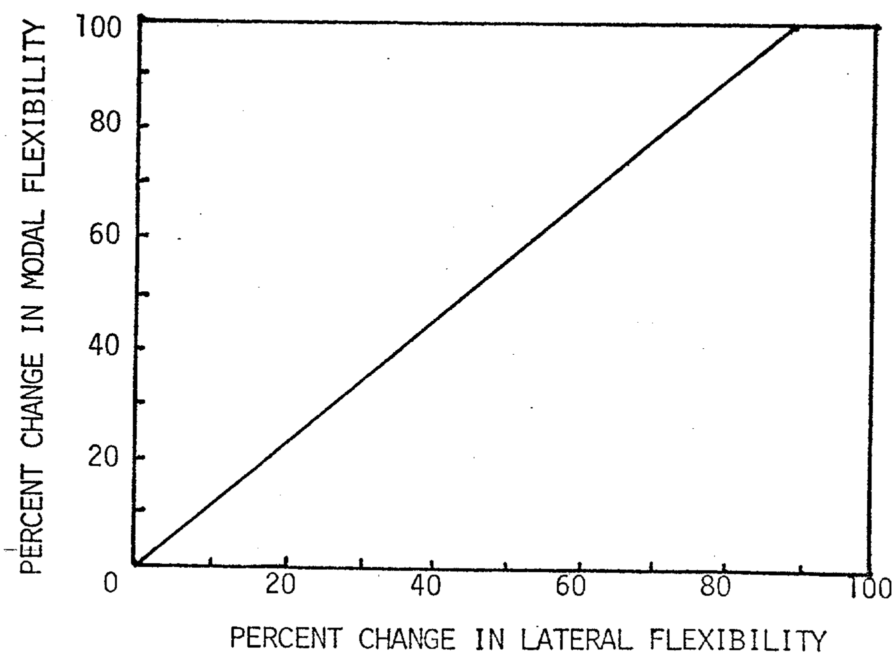


FIGURE 2 CHANGES IN MODAL FLEXIBILITY vs CHANGES IN LATERAL FLEXIBILITY

Figure 6

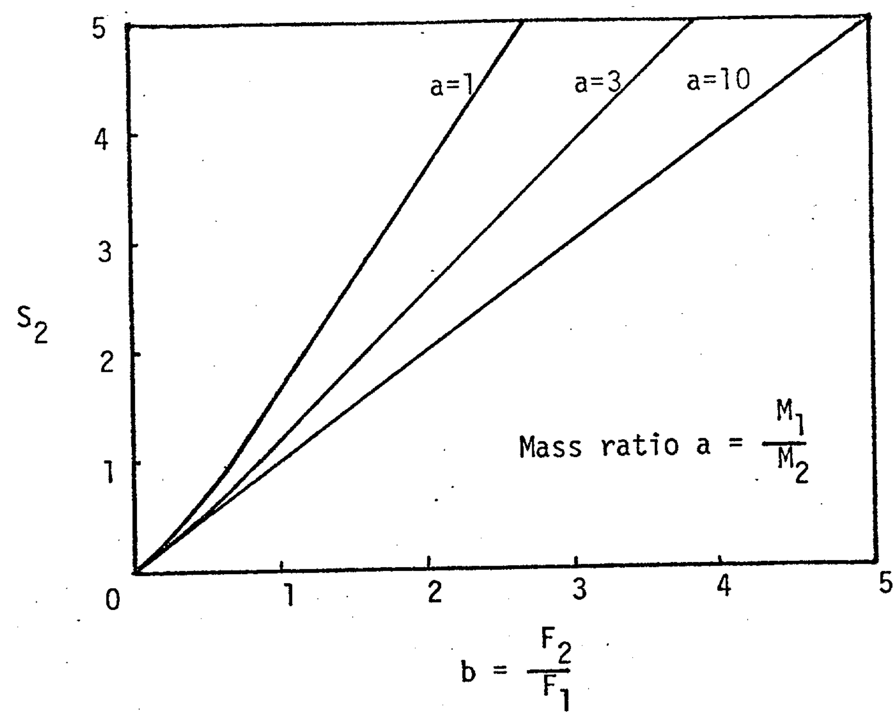


FIGURE 3 BOTTOM MODAL FLEXIBILITY vs LATERAL FLEXIBILITY

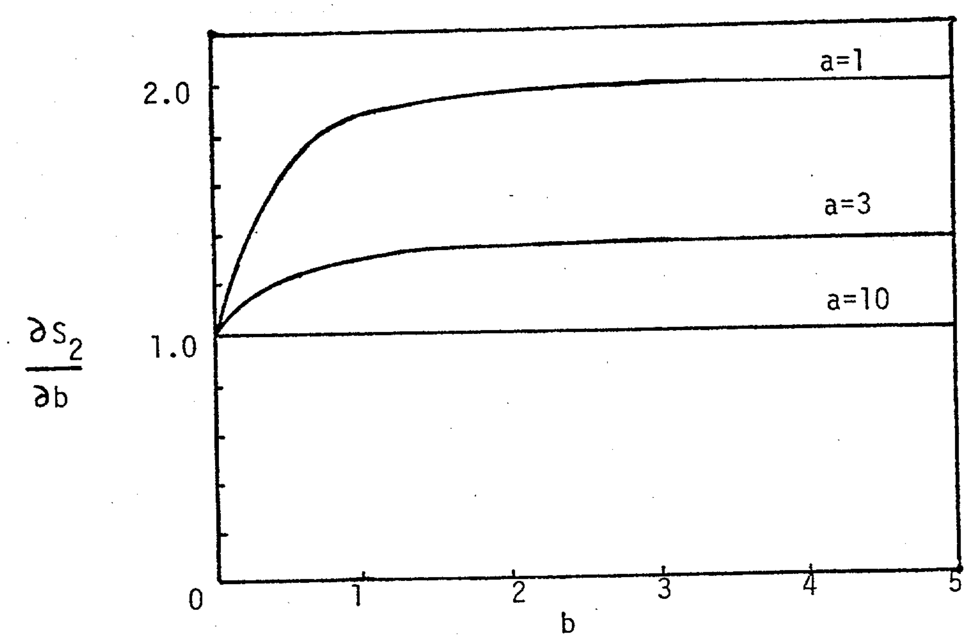


FIGURE 4 VARIATIONS OF THE BOTTOM MODAL FLEXIBILITY WITH RESPECT TO LATERAL FLEXIBILITY RATIO

As the mass ratio reduces and gets to a value like 1, there's a significant deviation between the modal flexibility and the lateral flexibility, and obviously in the case of an offshore platform, you're probably accounting for the deck mass effects, in this region of 3, maybe a little away from there.

That same result is captured in a different plot I prepared, a derivative of the slope with respect to B plotted against B. You find that the modal flexibility changes when you have a large mass ratio.

On the other hand, when you have a lower mass ratio, there is a linear proportionality, but the proportionality constant is different from 1, it's some other value. It becomes 2 when the mass ratio is 1.

The region of this plot we are interested in is the situation where the flexibilities of adjacent bays are on the order of 1.

In a typical offshore jacket platform you're not going to have flexibility at the top bay five times as much as the flexibility at the bottom bay. So you're talking about regions like so where there could be a non-constant proportionality.

Figure 8 talks about a very simple 2-degree of freedom system. These results will be quite different for a multi-degree of freedom system greater than 2.

In summarary, 100 percent increase in lateral flexibility of a bay implies probably around a 10-percent change in period, but a permanently high 110-percent increase in the modal flexibility. Also, a 50-percent change in the top mass implies a 10-percent increase in period.

On the other hand, just a 5-percent change in modal flexibility. That's why the modal flexibility parameter, is able to get rid of the effects of deck-mass changes.

Figure 9 provides some results for a multi-degree of freedom system example. We made a planar truss analysis on 18-degree of freedom dynamic system. This is the Southern California structure that is in place today, it's in about 100 feet of water -- 150 feet total structural height. We modeled the foundation in terms of some equivalent beam elements. The member masses are lumped at the end of the

RESULTS FOR TWO DEGREES OF FREEDOM SYSTEM

1. 100% INCREASE IN LATERAL FLEXIBILITY OF A BAY
   - 10% INCREASE IN PERIOD
   - 110% INCREASE IN MODAL FLEXIBILITY

2. 50% INCREASE IN TOP MASS
   - 10% INCREASE IN PERIOD
   - 5% DECREASE IN MODAL FLEXIBILITY

Figure 8

MULTI-DEGREES OF FREEDOM SYSTEM

PLANAR TRUSS ANALYSIS OF A 18 DEGREES OF FREEDOM STRUCTURE

MODELLING CHARACTERISTICS:

1. FOUNDATION STIFFNESSES ARE ACCOUNTED FOR
2. MEMBER MASSES ARE LUMPED AT THE ENDS OF THE MEMBER
3. ADDED MASS EFFECTS ARE INCLUDED
4. DRAG FORCES AND DAMPING ARE NEGLECTED

Figure 9

members. The added mass effects are included, and the drag forces and damping are neglected.

Figure 10 is basically a picture of that platform. This was actually designed according to ABI specifications for earthquake and wind and the way it's loaded in that situation. Keep in mind that it's an x-braced system and basically, these are some results for simulating damages on this brace, the horizontal member, and on the main leg of the foundation in Figure 11. The fundamental period of the structure is around 1.6 seconds in the undamaged state. The modal flexibility parameters for each of the four bays in the structure are listed in the first column, lateral flexibility is listed in the second column. You should keep in mind that in top bay the modal flexibility will always be 1, because you're normalizing.

What happens when one of the braces, a single brace fails? I guess it's a sort of re-enforcing what Dr. Rubin has found. That is, there's probably an insubstantial change in fundamental periods, a 1.67 percent change.

On the other hand, in this particular bay, there's a 45-percent change in the modal flexibility and a very similar change in the lateral flexibility. So in a sense the modal flexibility change reflects the lateral flexibility change. For all the other bays the changes are less than 1 percent. That's very, very small compared with the large change in the case of the second bay.

What happens if the main leg fails? It is more of an academic exercise because if the main leg fails you will obviously know that something has gone wrong with the platform.

Still, I think you will find a 70 percent change in the period. You also find a rather uniform change in modal flexibility parameters right through the structure and a lateral flelxibility change as well. But in this case you will find there is no one-to-one relationship between the modal flexibility change and the lateral flexibility change.

That is the important thing to keep in mind, the reason being that there is a rotational rigid body motion of the platform. So the lateral flexibility change is associated with only the deformation characteristics, not with the overall rotation of the structure.

In the case of a multiple member failure, if you have two X braces, you find that there is a very good discrimination

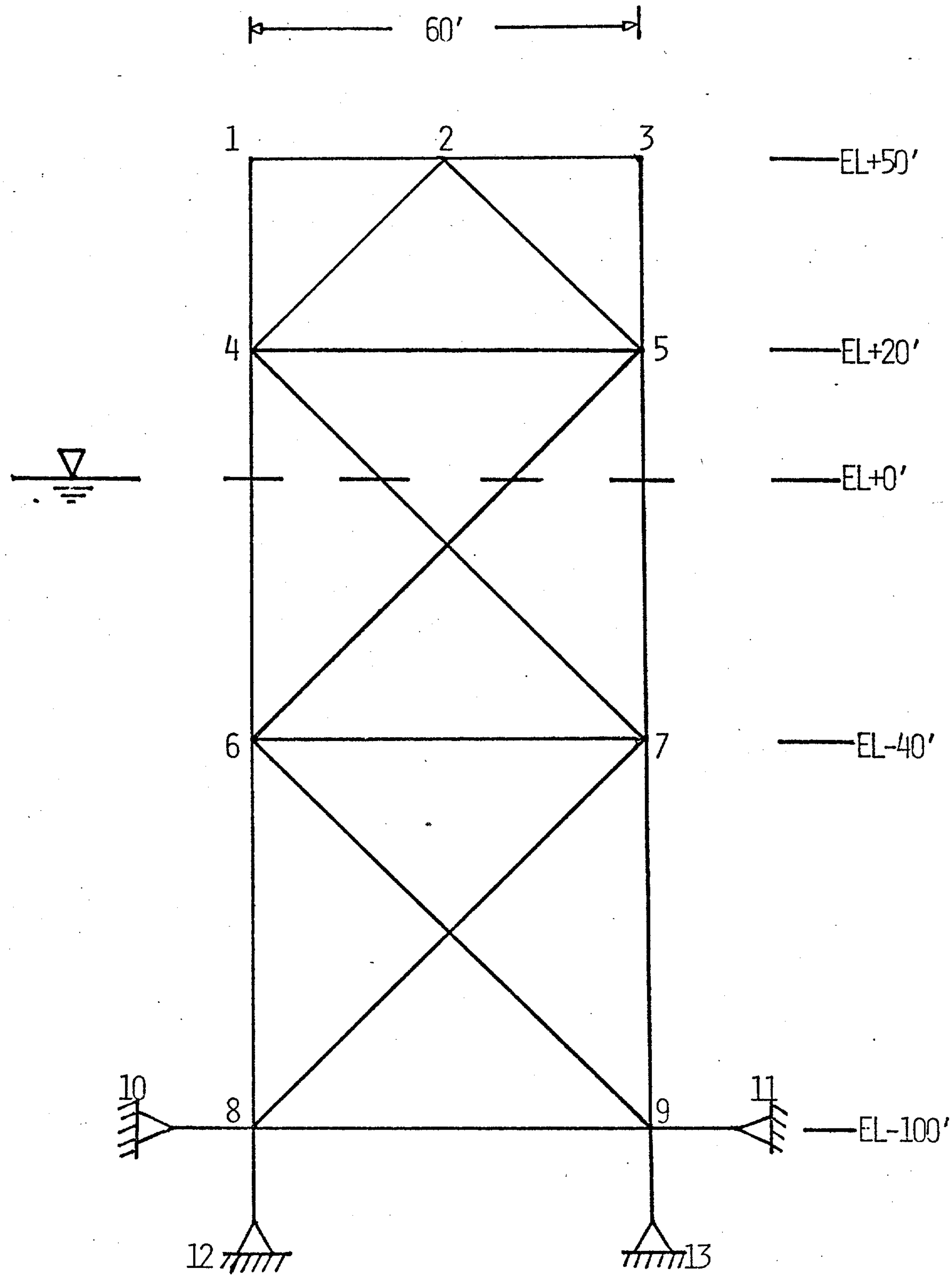


FIGURE 5 TRUSS STRUCTURE

DAMAGED CONDITION	PERIOD (SEC.)	MODAL FLEXIBILITY	LATERAL FLEXIBILITY
UNDAMAGED	1.565	1.000 2.419 2.086 1.718	1.141 2.764 2.285 1.734
MEMBER 4-7 (X-BRACE)	1.670(+6.7%)	1.000 3.506(+44.9) 2.078 1.697(-1.2%)	1.141 4.037(+46.1%) 2.285 1.734
MEMBER 6-8 (MAIN LEG)	2.644(+69.0%)	1.000 2.094(-13.4%) 1.239(-40.6%) 0.365(-78.8%)	4.833(+323.6%) 10.147(+267.1%) 5.977(+161.6%) 1.734
MEMBERS 4-7 AND 7-8 (X-BRACES)	1.738(+11.1%)	1.000 3.368(+39.2%) 2.857(+37.0%) 1.711	1.141 3.902(+41.2%) 3.066(+34.2%) 1.734
50% INCREASE IN DECK MASS UNDAMAGED	1.871(+19.6%)	1.000 2.413 2.053(-1.6%) 1.645(-4.2%)	1.141 2.764 2.285 1.734

Figure 11

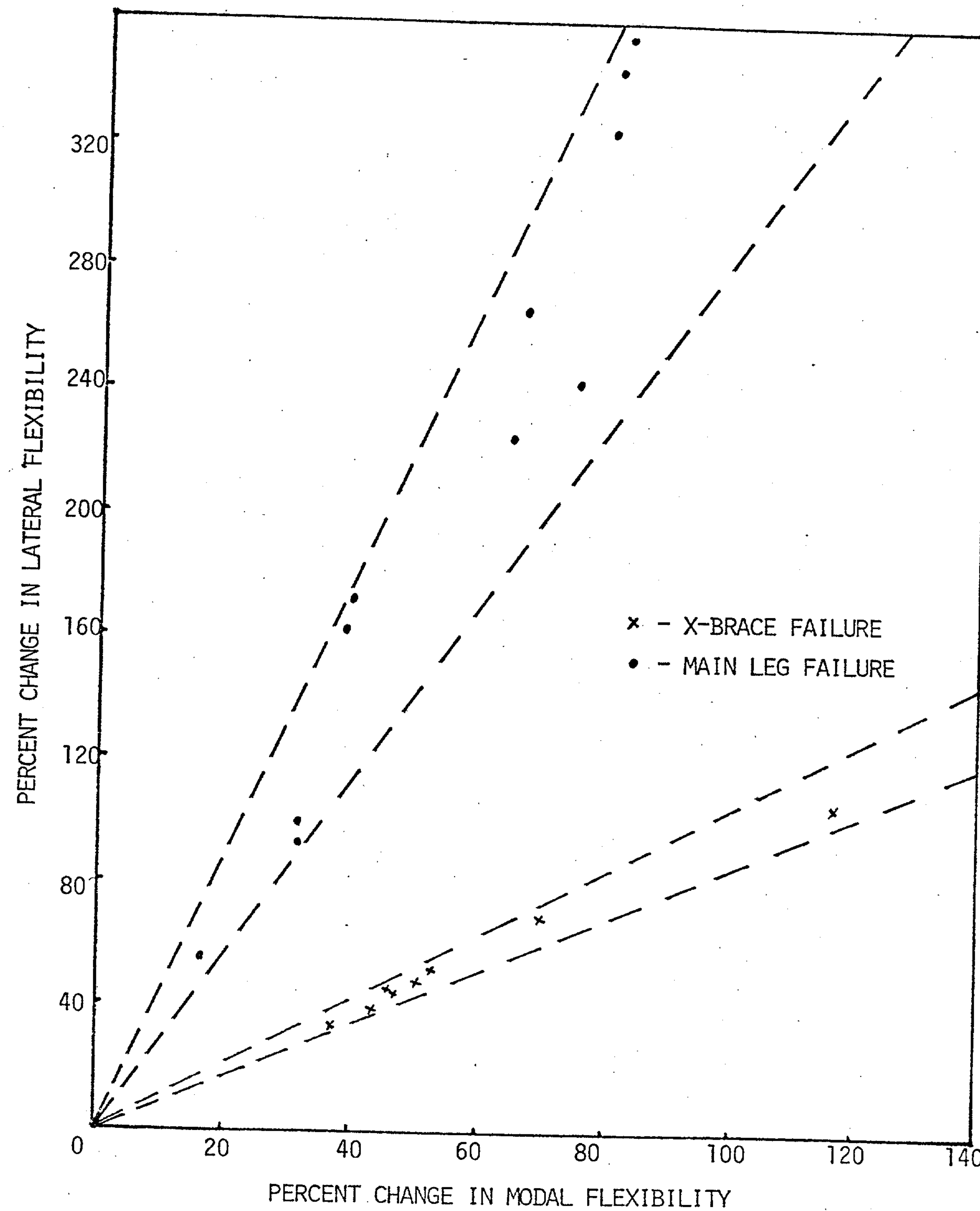


FIGURE 6 LATERAL vs MODAL FLEXIBILITY FOR MULTI DEGREES OF FREEDOM SYSTEM

Figure 12

power of the method - if you find a 39 percent change in this bay, a 41 percent change, very close, a 37 percent change and a 34 percent change in the other bay. So once again you find that, in this situation, discrimination is possible as well as it was possible in the previous case. But in this case you will find the fundamental period changes are also higher, around 11 percent.

And the final example is the 50 percent change in the deck mass. I guess a 50 percent change in deck mass is a very, very large amount. You are probably going to be uncertain in estimating deck masses in the 10 percent range.

Given a situation like this, it would imply a 20 percent change in the fundamental periods, but a very, very small change in the flexibilities, and I think that is the essence of the method.

Figure 13 summarizes the results of this very small study. One would say that the modal flexibility gives a reasonably good indication of changes in the lateral flexibility.

We find that multiple member failures can be detected. I am not saying this is a conclusive result, but this worked on the particular structure we looked at.

We also found -- and this was a result we didn't present so far -- that you cannot detect horizontal member failure. That is because it doesn't contribute, as Dr. Rubin pointed out, to the lateral flexibility. So it doesn't contribute to the modal flexibility.

We find that main leg member failure can mask the detection of an X brace member failure, which means if you have a main leg member failure and at the same time an X brace member failure, you are not going to be able to detect the X brace member failure. You can, provided you also measure the vertical load.

Multiple X brace member failures can be distinguished from main leg member failures by using the vertical modes.

Mass effects due to marine growth or deck mass changes are insignificant. We lowered the masses by 10 percent below water, and we have found the scale changes are insignificant.

Figure 14 shows a very unsophisticated backup type of analysis we carried out to track the sensitivity of the

<u>RESULTS OF MULTI-DEGREES OF FREEDOM SYSTEM</u>

1. MODAL FLEXIBILITY GIVES A GOOD INDICATION OF CHANGES IN LATERAL FLEXIBILITY
2. MULTIPLE X-BRACE MEMBERS FAILURE CAN BE DETECTED
3. HORIZONTAL MEMBER FAILURE CANNOT BE DETECTED
4. MAIN LEG MEMBER FAILURE CAN MASK DETECTION OF X-BRACE MEMBER FAILURE
5. MULTIPLE X-BRACE MEMBERS FAILURE CAN BE DISTINGUISHED FROM MAIN LEG MEMBER FAILURE BY USING THE VERTICAL MODAL AMPLITUDES
6. MASS EFFECTS DUE TO MARINE GROWTH OR DECK MASS CHANGES ARE INSIGNIFICANT

Figure 13

ERROR ANALYSIS

USING $X_i = \overline{X}_i + \Delta X_i$

WHERE ΔX IS THE ERROR IN ESTIMATING X

CAN FIND $S_i = \overline{S}_i + \Delta S_i$

ERROR OF 1% IN ALL THE MODAL AMPLITUDES RESULTS IN

ERROR OF:

20% IN S_2

18% IN S_3

17% IN S_4

Figure 14

modal flexibility parameter to errors in estimation of the fundamental mode shape.

Let's assume there are two kinds of errors we want to look at -- a bias error, or systematic error, and a random error, which is very often taken to be Gaussian.

Assume first that we have a bias. Assume that you have an actual measurement. The true mode shape is the measured mode shape plus some error terms.

You can find that for a change in flexibility, as a result of this error in the mode shape value, and if you take a 1 percent error -- let me qualify this as well. I took the worst case scenario. I said, let's assume the systematic error is the most unfavorable that we can get.

If I do that, then a 1 percent error in the modal value would imply a 20 percent error in the second flexibility and an 18 percent error in the third flexibility and a 17 percent error in the fourth flexibility. It is a very rough calculation, but it shows that a small error in the modal value means a large error in flexibility.

Figure 16 shows a second analysis which essentially assumes that I will have a variance. I have a random error. I quantify this random error through a standard deviation and the mean, and I want to obtain the standard deviation of the computed flexibility parameter.

Now you have basically a nonlinear equation relating the modal values to the flexibility parameters. In order to compute, therefore, an estimate of the error in the modal flexibility, one has to linearize that equation, at least through a simple analysis.

So after having gone through a simple linearization procedure, which is a fairly standard statistical technique, we carry out the analysis.

We looked at two types of standard deviations. One was assuming that you had a constant standard deviation, a constant random error right through the depths of the structure, and we chose the value at the top to give a coefficient of variation of 1 percent.

Now you find that the coefficient of variation of flexibility is on the order of 11 percent. There is an order of magnitude change in this calculation.

Note: Text does not reference a Figure No. 15.

SENSITIVITY ANALYSIS

ASSUMPTION	MODAL AMPLITUDE		MODAL FLEXIBILITY	
	NODE	COEFFICIENT OF VARIATION	BAY	COEFFICIENT OF VARIATION
CONSTANT STANDARD DEVIATION	1	0.010	1	—
	2	0.012	2	0.110
	3	0.019	3	0.113
	4	0.042	4	0.110
STANDARD DEVIATION INVERSELY PROPORTIONAL TO THE MEAN AT EACH NODE	1	0.010	1	—
	2	0.014	2	0.129
	3	0.036	3	0.194
	4	0.177	4	0.209

Figure 16

Obviously, now the constant standard deviation is probably not a realistic model. Possibly a better modal for the standard deviation or random errors is one in which you assume the standard deviation to be inversely proportional to the mean value of the mode, meaning that there is a greater uncertainty in estimating the mode shape at the bottom of the structure than there is at the top.

So if I carry out that kind of analysis, once again assuming a coefficient of variation to be 1 percent on top, we find in fact a greater effect at the bottom in all these modal flexibilities. We have 12 percent, 19 percent, and 20 percent.

I guess the lesson here is that very small errors in estimating the mode shape can imply very large errors in the flexibility parameter.

This analysis can be questioned, for at least one reason, that I assume each of the X's, the modal values, are independent random variables. If I account for the fact that there is some conflict between these random variables, then the total error will probably go up and down and maybe Dr. Rubin's number that he put up - what, 10 percent - could be a realistic assessment.

But still I think the issue in there is a 10 percent change, and that is probably going to mask the changes of about 20, 30, or 40 percent or more in flexibility, which indicate damage. So we want to try to sharpen our understanding of the mode shapes as much as we can.

I would like to move on to some potential research efforts. Before I get into the specifics of two areas that I have in mind, I would like to stress that this correlation of modal and lateral flexibility needs to be studied a lot more in realistic platforms; for example, on an eight-leg Gulf of Mexico type platform, maybe a Cognac type platform. But we need to do that to see what happens.

We also need to see what happens if you have four instruments on an eight-legged platform, and you define your flexibility based on those four instruments. How does that flexibility, that average measurement, really indicate the lack of flexibility of the total structure?

You also want to look at partial member damages. I think in all of these sensitivity analyses we have done and in most of the Round Robin type applications, we have assumed a member has broken.

FUTURE RESEARCH

1. IMPROVEMENTS IN MEASURING INSTRUMENTS
2. DEVELOPMENT OF MORE EFFICIENT AND ACCURATE MODE SHAPE ESTIMATION ALGORITHMS

FIGURE 17

CONCLUSION

1. CHANGES IN MODAL FLEXIBILITY DOES REFLECT THE CHANGES IN LATERAL FLEXIBILITY
2. MASS EFFECTS ARE INSIGNIFICANT
3. REQUIRES ACCURATE MODE SHAPE ESTIMATION

FIGURE 18

Now if you go back and look at some of the literature in the offshore area, people have looked at damage in terms of two or three models; e.g., the brittle model and the ductile model.

The brittle model assumes you have no residual stiffness. The ductile model, on the other hand, shows that you still have some residual stiffness.

Experience in the Gulf of Mexico has shown that the ductile redundant model is probably more realistic, at least from the experience in the Gulf of Mexico. So I guess we need to do some work in terms of seeing how this method can apply to at least partial member damages, not complete damage.

Figure 19 identifies modal methods. We are considering two quick possible research topics which we think are important. We have stressed over and over again the importance of the accuracy of the mode shape estimates.

One of the principal goals of each a method we want is to develop response data, reduction and analysis techniques for the measurement of mode shapes.

There are several ways in which one can do it. Conventional auto correlation of periodgram-based spectral estimates are the most popular, and I suspect the ones have been used in most of the world in terms of nondestructive evaluation, including, I believe Dr. Rubin's work, is based on that.

The number I have here is based on the report that Dr. Rubin produced a couple of years back. It said the accuracy of relative amplitudes for well-identified modes is about 5 to 10 percent. And I think he has also proven that that is probably a little low.

The other approach that should be considered is one that a member in this audience, Dr. Brad Campbell from Exxon, has developed as part of his PhD work at MIT a couple of years ago. That is the maximum entropy method of spectrum estimation.

We are specifically talking about the multi-channel estimation based on the work of Mike Briggs. A lot of this work has really been done at MIT. The claim made is that MEM techniques are high resolution, which means you can probably work with shorter data lengths, or, given the same data length, your uncertainty in the modal amplitudes is less.

MODAL IDENTIFICATION METHODS

KEY MEASUREMENT ISSUE: ACCURACY OF MODE SHAPE ESTIMATES

PRINCIPAL GOAL: DEVELOP RESPONSE DATA REDUCTION AND ANALYSIS TECHNIQUES FOR THE MEASUREMENT OF MODE SHAPES

CANDIDATE TECHNIQUES:

CONVENTIONAL AUTOCORRELATION OR PERIODOGRAM BASED SPECTRAL ESTIMATORS

- USED IN MOST PRIOR WORK, INCLUDING RUBIN AND COPPOLINO
- ACCURACY OF RELATIVE AMPLITUDES FOR WELL IDENTIFIED MODES 5-10%

MULTI-CHANNEL MAXIMUM ENTROPY METHOD

- WORK ON DEVELOPMENT OF MEM TECHNIQUES FOR OFFSHORE APPLICATIONS PIONEERED AT MIT
- LIMITED APPLICATION HAS SHOWN THAT FROM AN EFFICIENCY AND ACCURACY STANDPOINT IT COULD BE SUPERIOR TO CONVENTIONAL SPECTRAL TECHNIQUES

MULTIPLE RESPONSE SHAPE VECTOR

- BURKE AND ASSOCIATES, 1981-82
- ACCURATE DETERMINATION OF MODE SHAPES AT FREQUENCIES DOMINATED BY A SINGLE MODE
- INADEQUATE IDENTIFICATION WHEN TWO OR MORE MODES CONTRIBUTE SIGNIFICANTLY

IBRAHIM TIME-DOMAIN METHOD

- APPLICATION WITH RANDOMDEC INPUT
- AEROSPACE EXPERIENCE, NONE IN OFFSHORE NDE APPLICATIONS
- OFFSHORE DAMPING WORK AT MIT

Figure 19

Its application has been rather limited. At least, in mode shape work, it has been very limited. But it has been shown that it could be superior to conventional spectral techniques based on this analysis of a "lollipop" type of a platform before these measurements were made.

If you talk to the Electrical Engineering types at MIT, they will probably be talking about the fact that MEM is the best method available, and they will not use anything else.

There is another approach that a few people have really looked at -- Burke & Associates -- a method called multiple response shape vector. They have found accurate determinations of mode shapes at frequencies dominated by a single mode.

They have found that when you have more than one mode contributing to the response at a particular frequency, then the identification of the mode shape is inadequate. They have problems.

A final candidate that probably deserves evaluation at the same level as the other methods, and probably a very good method in itself, is the Ibrahim time domain method.

The key issue here is that the inputs to the Ibrahim time domain method has to be based on the random dec input. In the case of the random response vibration problem, its primary experience in mode shape work has been in the aerospace and NDE applications area, but we have done some work at MIT to try to estimate damping with the method, and it seems like a promising approach.

Figure 20 shows what would be the research emphasis of some work like that?

The first thing one needs to do is carry out a very simple comparative study of the algorithms by applying them to simulated data, the Round Robin test type of data, where you have pretty good control over the input and the output, and actual offshore platform data.

We also need to quantify their capabilities in terms of the accuracy of the algorithms, the computational efficiency for processing enormous amounts of data that might become available. We also need to take into account the realtime capabilities of these algorithms.

RESEARCH EMPHASIS:

COMPARATIVE STUDY OF ALGORITHMS BY APPLICATION TO:

- SIMULATED DATA
- ROUND ROBIN TEST DATA
- ACTUAL OFFSHORE PLATFORM DATA

QUANTIFICATION OF CAPABILITIES

- ACCURACY OF ALGORITHMS
- COMPUTATIONAL EFFICIENCY FOR PROCESSING ENORMOUS AMOUNTS OF DATA
- REAL-TIME CAPABILITIES

FURTHER DEVELOPMENT

- SYSTEMATIZATION TO MINIMIZE OPERATOR INTERVENTION
- ALGORITHMIC IMPROVEMENT THROUGH INTEGRATION AND FURTHER DEVELOPMENT

FINAL PRODUCT:

ACCURATE, EFFICIENT AND SYSTEMATIC MODAL IDENTIFICATION METHOD

WELL DOCUMENTED COMPUTER PROGRAM WITH GUIDELINES FOR USAGE

Figure 20

As these types of work get done, futher development could be to add systemization to minimize operator intervention.

There are very few parameters to define in the identification problem, and one area which is very crucial -- people who have worked in that area will realize that there are significant opportunities for algorithmic improvement, which arise because of the integration of different methods. And I think that is equally true in the case of mode shape extraction.

For example, can MEM be combined with response shape records, or can MEM be combined with the ITD? You get increased and improved capabilities of these basic methods.

Figure 21 covers the Computer Based Damage Assessment System. The final research area is a little fancy. Nonetheless, I think it is meritorious. The key issue in an NDE type of test is identification of the presence of failure on a structure, discrimination of the degree of damage and the location of damage.

You are all familiar with those basic issues. The principal goal of this research would be to develop a rational and systematic computer-based damage assessment system utilizing artificial intelligence techniques for evaluating the safety and reliability of offshore platforms.

Now, let's get into the details. The relevance of this type of research stems from the fact that damage assessment from NDE evaluations, such as flexibility monitoring, requires skills. That is one thing we really need to keep in mind.

If I give the same data, instead of to Dr. Rubin, to John Blow down the street, can he make that assessment? Based on the flexibility at time point 1 and time point 2, can he say where is the damage, how much is the damage, and so on?

I think transfer of this complex decision-making process requires a close working relationship with experienced engineers. These experienced engineers aren't all that many. There are very few of them, like Dr. Rubin or Dr. Yang, available to make these analytical type deductions.

So what we need is some way to make damage assessment, possibly by an operator aboard a platform, which means the method should be foolproof.

Figure 22 illustrates a terminology called "knowledge-based expert systems theory." Although I am not an expert, I

COMPUTER-BASED DAMAGE ASSESSMENT SYSTEM

KEY ISSUE:

IDENTIFY THE PRESENCE OF FAILURE ON A STRUCTURE

DISCRIMINATION BETWEEN FAILURE AND NON-FAILURE CONDITIONS

DISCRIMINATION OF DEGREE OF DAMAGE

DETERMINATION OF LOCATION OF DAMAGE

PRINCIPAL GOAL:

DEVELOP A RATIONAL AND SYSTEMATIC COMPUTER-BASED DAMAGE ASSESSMENT SYSTEM UTILIZING ARTIFICIAL INTELLIGENCE TECHNIQUES FOR EVALUATING THE SAFETY AND RELIABILITY OF OFFSHORE PLATFORMS

RELEVANCE:

DAMAGE ASSESSMENT FROM NDE EVALUATIONS SUCH AS FLEXIBILITY MONITORING REQUIRES SPECIALIZED SKILLS

TRANSFER OF THIS COMPLEX DECISION MAKING PROCESS REQUIRES CLOSE WORKING RELATIONSHIP WITH THESE EXPERIENCED ENGINEERS

PROBLEM COMPOUNDED BECAUSE OF ONLY FEW EXPERTS

NEED SOME WAY TO MAKE DAMAGE ASSESSMENT POSSIBLE BY AN OPERATOR ABOARD A PLATFORM (METHOD SHOULD BE FOOL PROOF)

Figure 21

KNOWLEDGE-BASED EXPERT SYSTEMS THEORY

ALGORITHMS VERSUS HEURISTICS

PROGRAM: COLLECTION OF RULES
IF (premise) THEN (action)
DOMAIN EXPERT KNOWS PREMISES AND ACTIONS

ALGORITHM: SPECIFY EXACT SEQUENCE OF RULES
GUARANTEE COMPLETENESS; EVERY PREMISE HAS ACTION
GUARANTEE UNIQUENESS; EVERY PREMISE HAS ONE ACTION

HEURISTIC PROGRAM: INFERENCE MACHINE SCHEDULES RULES
IF INCOMPLETE, NO ACTION; ADD RULES
IF NOT UNIQUE, PROGRAM REUTRNS ALL CHOICES

EXPERT SYSTEMS

COMPUTER PROGRAMS THAT PERFORM INTELLIGENT TASKS
CURRENTLY PERFORMED BY HIGHLY SKILLED PEOPLE

COMPONENTS: KNOWLEDGE BASE
INFERENCE MACHINE: DEDUCES ANSWER FOR GIVEN PROBLEM OBSERVATIONS USING KNOWLEDGE IN KNOWLEDGE BASE
FUZZY SET THEORY: UNCERTAINTY IN OBSERVED DATA
UNCERTAINTY IN RULES
SYSTEM COMPLEXITY

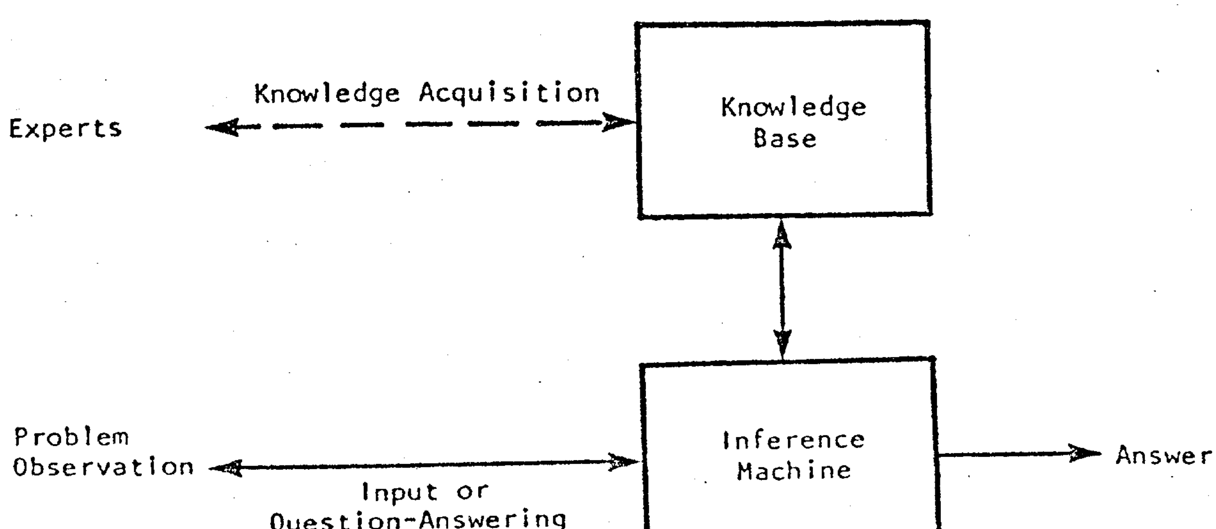


Figure 22

would like to summarize some of the basic notions in that area.

I think the key distinction one has to make is between algorithms and heuristics. Most of our engineering type calculations are algorithms, not heuristic.

For example, a computer program has a connection of rules which, in essence, take you from step 1 to step 2 to step 3. You basically have an "if/then" -- if the premise is satisfied, then you do that. Now the domain expert, which means in this case the NDE expert, knows the premises and the actions.

An algorithmic type rule specifies the exact sequence of rules, the logical sequence. You have to gather the completeness of the computer program, and you need to gather the uniqueness of the program, which means 2 plus 2 has to be equal to 4; it can't be equal to 4 or 5. And the 4 or 5 situation arises when you have to make decisions.

So a heuristic program is different from an algorithmic program. It essentially has an inference machine which schedules the roots. So this machine takes over the role of scheduling the rules. The program can be complete in theory, and it can be nonunique also in theory.

An expert system basically is therefore a computer program that performs intelligent tasks currently performed by highly skilled people. The components to that system are the knowledge base. This is a knowledge base which consists of knowledge acquired from experts. This will be a collection of rules.

For example, if the flexibility changes and the lateral mode is following, then we can assume that the following member on the following face has failed.

That's the kind of knowledge you want to put into the knowledge base. So, you have all these inputs coming in to that problem observation phase.

Then, you have the inference machine, which tries to give you an answer.

I think the critical issue here is that the answers are not straight forward. You don't have a unique answer or a unique situation. Therefore, you have uncertainty in observed data. You have to account for uncertainty in the rules. And you have to account for the fact that, as the system gets more and more complex, the decision making is going to get more and more complex.

In that situation, the heuristic system is brought in to provide some kind of an answer in the gray areas.

Based on all the knowledge I have, I can probably say that this particular member at this particular location has failed, and this failure can be quantified with this much amount of confidence -- 80 percent, 90 percent, or thereabouts.

Figure 23 shows several problem observations. It could be the random dec input; it could be the observation of frequency changes in the fundamental lateral and torsional modes which provide some basis for discrimination of member failure conditions and mass changes; and it could be the flexibility monitoring of fundamental lateral and torsional modes. You can also do above-water observations of local brace mode frequency shifts and associated shape changes providing qualitative indication of brace failures.

The second reason for this viewgraph is that there's a report by Dr. Rubin in which he carries out so-called modal sensitivity analysis, which essentially contains a lot of rules on which to base an expert system.

So, what will the research emphasis be in this area?

In Figure 24, we see construction of rules from a modal sensitivity analysis would be obviously structure-dependent -- the influence of multiple member severences in the construction of the rules, the uncertainties in the modal identification process, the complexity of the structural system having obviously special rules for each structural types. We need to develop and acquire computer codes used in the area of expert systems. Several of them exist.

You'll want to test and apply this, first of all, to very simple systems. I should point out this is still a research area, so simulated data, Round Robin test data, and actual offshore platform data could be used.

So finally, if everything goes well, we will have a methodology for computer-based damage assessment. You should have an assessment of the capabilities for prototype implementation -- that's a crucial area, I guess. And we need a well-documented computer code.

PROBLEM OBSERVATIONS

OBSERVATION OF NATURAL FREQUENCY CHANGES IN FUNDAMENTAL LATERAL AND TORSIONAL MODES PROVIDES SOME BASIS FOR DISCRIMINATION OF MEMBER FAILURE CONDITIONS AND MASS CHANGES

OBSERVATION OF ABOVE-WATER MODE SHAPE SENSITIVITY OF THE FUNDAMENTAL LATERAL AND TORSIONAL MODES GIVES EVIDENCE OF THE FACE ON WHICH A DIAGONAL BRACE HAS BEEN SEVERED, OR THE CANDIDATE CORNERS ASSOCIATED WITH LOSS OF MAIN LEG BOTTOM SUPPORT

FLEXIBILITY MONITORING OF FUNDAMENTAL LATERAL AND TORSIONAL MODE SHAPES PROVIDES THE MOST EFFECTIVE MEANS FOR LOCATION OF DIAGONAL AND HORIZONTAL SEVERANCES

ABOVE-WATER OBSERVATION OF LOCAL BRACE MODE FREQUENCY SHIFTS AND ASSOCIATED SHAPE CHANGES PROVIDES A QUALITATIVE INDICATION OF BRACE FAILURES

(RUBIN AND COPPOLINO, 1981)

Figure 23

RESEARCH EMPHASIS

CONSTRUCTION OF RULES FROM A MODAL SENSITIVITY ANALYSIS

INFLUENCE OF MULTIPLE MEMBER SEVERANCES, UNCERTAINTIES IN MODAL IDENTIFICATION PROCESS (ESTIMATION ALGORITHM, EQUIPMENT-INDUCED NOISE, CROSS-AXIS SENSITIVITY AND MISALIGNMENT OF ACCELEROMETERS), MASS CHANGES

COMPLEXITY OF STRUCTURAL SYSTEM

DEVELOPMENT/ACQUISITION OF COMPUTER CODES

TESTING AND APPLICATION

- SIMULATED DATA
- ROUND ROBIN TEST DATA
- ACTUAL OFFSHORE PLATFORM DATA

FINAL PRODUCT

METHODOLOGY FOR COMPUTER-BASED DAMAGE ASSESSMENT SYSTEM

ASSESSMENT OF CAPABILITIES FOR PROTOTYPE IMPLEMENTATION

WELL DOCUMENTED COMPUTER CODE

Figure 24

DR. PERRONE: Is this a planned item or something you'd like to do if you had the funding?

DR. SUNDER: No, it's planned -- the last two items.

DR. PERRONE: Would that be with the cooperation of the AI group at MIT.

DR. SUNDER: Yes. We would like to do that. This is an area where a lot of civil engineers right now are very interested.

Stephen Spence at Carnegie-Mellon has been doing some work in the area. James Yao at Purdue has been doing some. We see this as one possibility.

MR. BOLELHO: In terms of a practical application, what are your ideas?

Dr. Rubin expressed some ideas about practical applications. What are your ideas on that to develop a system that could be used in a platform? You're talking about platform dependence there. There are very few platforms outfitted with the chutes, as Dr. Rubin mentioned.

What would you do in terms of the system platforms?

DR. SUNDER: The answer is not clearcut.

Dr. Rubin has taken the more practical approach, where he says, "Let's try and put them on the platform today and work with them and see how they work."

What I have talked about here is basically a more research-oriented approach, with the result that practical results will become available if and when the research gets done.

But I think there is no need for practical applications to wait till research gets done. That's a never ending process.

DR. BOLELHO: In terms of an on-board system, do you have in mind having a computer there?

DR. SUNDER: That's right.

My objective is to have an on-line identification algorithm, to have a system identification program in a computer software package which will be on-board the offshore platform.

MR. BOLELHO: You would also have several accelerometers along the depth of the platform.

DR. SUNDER: Conceptually, it's identical to Dr. Rubin's proposal.

MR. BOLELHO: I think he has a different idea. I think he has a package that would go down and operate and would take measurements.

Apparently you're talking about having something that would stay there. Dr. Rubin's concept is something that could be transferred from platform to platform, as long as everything is standardized.

Apparently, you're talking something fixed, with several transducers.

DR. SUNDER: No. We need to keep it in proper perspective. When I talked about rules being platform-specific, I think he would agree with me that the discrimination rules that might apply to a particular platform could be different for a more complex platform in terms of the numbers and the flexibility changes, in terms of the particular rules, where you have an 8- or 16-legged platform versus a 4-legged platform. There are certain differences that you observe. That's something you need to keep in mind.

There are going to be some changes by platform type that will affect the knowledge base. And the rules in terms of information you provide for the inference machine would be Dr. Rubin's two values of flexibility, plus natural frequency, if that exists.

Dr. Yang's work on random dec gives you additional information. All that can be, but does not have to be, factored in.

We should keep in mind that each of the methods only provides partial information.

MR. BOLELHO: Perhaps you have to keep in mind, as well, the practicality of your ideas, because if you're saying you have to deploy a thousand-foot platform, you have to deploy a sensor at each level --

DR. SUNDER: I'm not saying that.

MR. BOLELHO: You gave me that impression.

DR. SUNDER: It can be factored in.

MR. BOLELHO: You gave me that impression -- everything would be on board and the system would be there.

CHARLES SMITH, MMS: On your first or second slide there, you showed the slanting of the parameter as a function of the ratio between two masses, using a two mass system. If you went to a more complex system, how would it affect that slant? Would it move back over?

DR. SUNDER: You have to be careful. I don't think we can really extend this system to a multi-degree frame system.

We really have to do the numbers for that system.

DR. RUBIN: The trends would be similar.

DR. SUNDER: I would assume so. Yes.

DR. BASDEKAS: At the end of your presentation, you indicated that a set of rules could be programmed in a computer and then come up with prediction.

Do you intend to derive those rules on the basis of parametric experimentation?

DR. SUNDER: A very good question.

I guess the simplest approach there would be through an extensive -- what one might call "sensitivity analysis" on a computer.

DR. BASDEKAS: Analytical? If you have that reliable a predictive tool, why do you have to go through the heuristic approach? Just go through the predicted one set out --

DR. SUNDER: What I'm saying is if you look at this particular platform that you have in mind, 8- platform in the Gulf of Mexico, and you're using some approach, you come up with a piece of information that through the modal sensitivity analysis, you came up with the fact that this implies a particular location of the damage.

Now this is clearly one tool, and it is not a heuristic model.

DR. BASDEKAS: The heuristic mode is not in lieu of solving the base problem.

DR. SUNDER: That's right.

DETECTION OF DAMAGES WITH SYSTEM IDENTIFICATION

Dr. Jackson Yang
University of Maryland

Dr. Sunder gave some background in this area. I guess I fall in the category of further development.

Figure 1 points out that the objective of our study is to use a system identification technique to do three things.

First, to determine the dynamic characteristics of the known structural design. From measured date, we're able to -- using the system identification technique, come up with the dynamic characteristics which means the eigenvalues and eigenvectors of the structure.

Second, knowing the eigenvalues and eigenvectors -- the direct characteristics of the structural system -- through system identification, we are able to come up with the matrices and, in turn, obtain the actual mathematical model.

This is sort of the inverse problem. Instead of starting off with a mathematical model, you start off with the physical system, and through measured data, are able to go backwards and come up with the mathematical model which represents that particular structural system.

Once you have this mathematical model, then, from looking at the mass, stiffness, and the damping matrices of the structure that has some damage in it, by looking at the changes in the mass, stiffness, and damping matrices of a structure that has some damage in it, by looking at the changes in the mass, stiffness, and damping matrices, we hope that we are able to detect the damage and possibly to find the location of the damage.

Originally, using the random decrement technique, we were just looking at an early warning type of detection of cracks and damages.

We never really did advocate that random dec would give you the exact, precise location of damage even though, with experience, you might have a good chance.

But hopefully, with a combination of system identification and the random decrement technique, we'll be able to not only detect damage, but also have a better chance of actually locating where the damage is.

OBJECTIVE

USE SYSTEM IDENTIFICATION TECHNIQUES TO

- DETERMINE THE DYNAMIC CHARACTERISTICS OF KNOWN STRUCTURAL DESIGN
- DEVELOP ACCURATE MATHEMATICAL MODEL
- DETERMINE THE LOCATION AND SEVERENESS OF STRUCTURAL DAMAGE

Figure 1

Figure 2 shows we work the approaches we have taken it two directions. One is the frequency domain, then the time domain.

The frequency domain approach is based on a thesis from one of my students, Dr. Robert Rhee, who is with the Naval Surface Weapons Center. He used the frequency domain, and looked at measured data and came up with a mathematical model. At that time I think Dr. Rhee advanced the State-of-the-Art from what Costerman did back at Cincinnati.

Since that time Costerman and Company has gone to Spectrodynamics, etc., and Nicolai and all the other companies have come up with some sort of spectrum analyzers that do some of these things. But here we hope to advance the State-of-the-Art a bit more by looking at it with the frequency domain in terms of non-linear curve-fitting methods and another approach using the linear regression method.

In the time domain, essentially we use an auto-regression method which many people use, but we are using this auto regression method with the random decrement technique. As a matter of fact we do a little cross-random decing, which I'll talk about in a few minutes. Hopefully we can come up with the mathematical model, the mass, stiffness, damping matrices and look for changes.

The next VuGraph is the important one that gives you the scenario as to exactly what I go through, the steps for the frequency domain, and the time domain. Let me describe to you the steps that you actually go through for the frequency domain. First of all, you have a structure as seen in Figure 3. You apply loading to your structure -- for instance, you can do it with hammers and what-not, and you get the structural response.

The same thing with the time domain. The time domain is a bit more flexible in the sense that if it's an offshore platform, for example, you can use the environmental kind of excitation. That's sufficient.

So in a sense in the frequency domain you really need to know the input, whereas in the time domain with the approach that we're talking, you don't need to know the input. Just use the environment type of excitation.

Now, with the structural response, in the frequency domain you take the response, you go through a spectroanalyzer FFT, you come up with an average frequency response.

APPROACH

- FREQUENCY DOMAIN :

  NONLINEAR CURVE FIT METHOD

  LINEAR REGRESSION METHOD

- TIME DOMAIN :

  AUTO-REGRESSION METHOD WITH RANDOMDEC

Figure 2

SYSTEM IDENTIFICATION

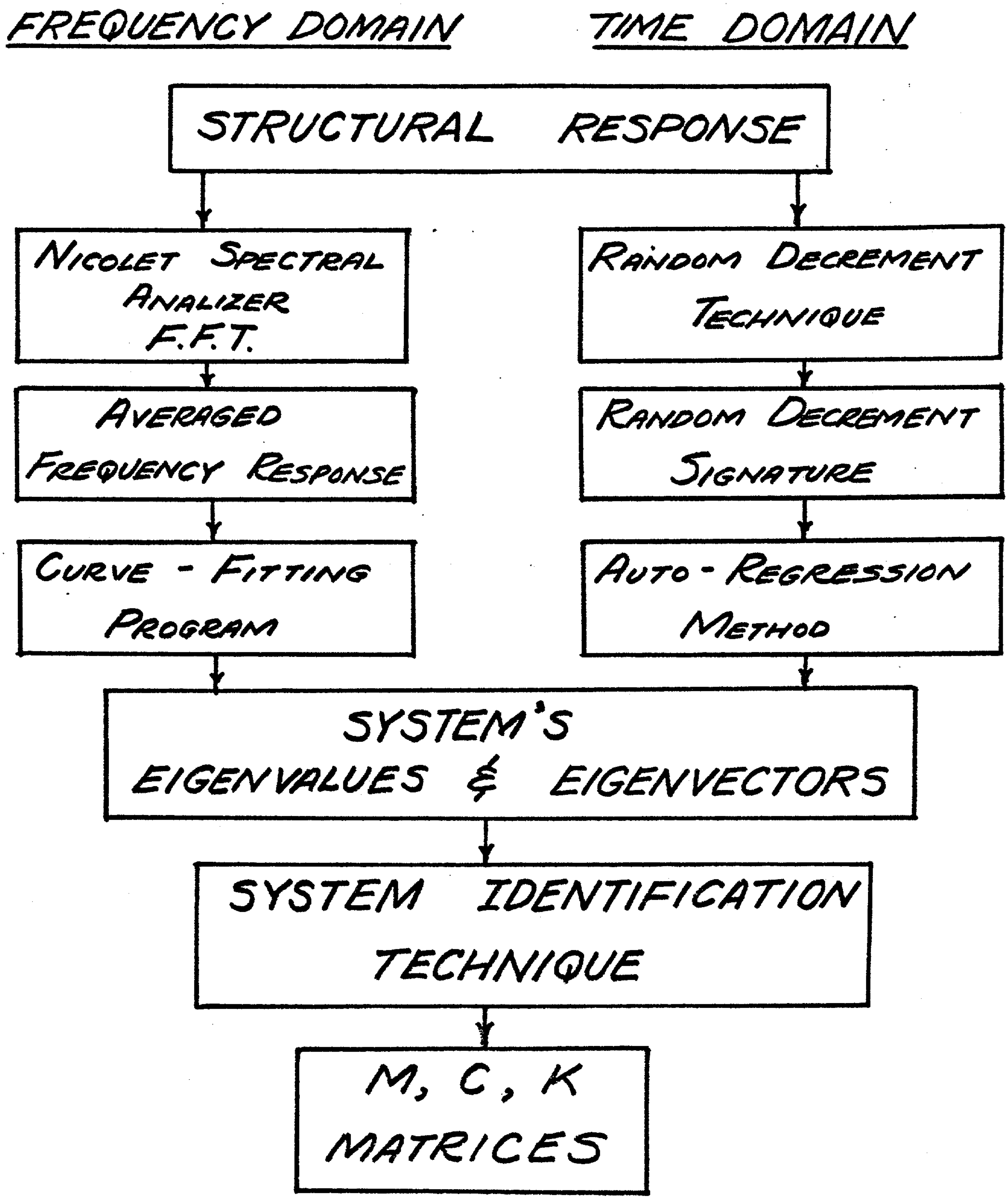


Figure 3

At this stage there are a number of ways you can obtain the system's eigenvalues and eigenvectors. For instance, in the classical way of doing it, before you had spectrum analyzers, you use FFT, then you look at the half-power points to get the damping and you pick off your peaks. Then of course, it gets a bit more sophisticated with the various new spectrum analyzers, and you have a curve where you do a curve-fitting.

However, in most of the spectrum analyzers we've been associated with, the curve-fitting techniques are such that they curve-fit one mode at a time.

Some of them use weighting functions to look at the influence of the other modes. Now we have come up with a non-linear curve-fitting technique in which we're able to curve-fit as many modes as you like. Of course there's a limitation. If you have 200 modes, that might be very time consuming on a computer, for those of you that have looked into this type of problem.

But, for instance, we have curve-fit modes, all at the same time. This is one contribution. Fortunately, excellent associates are working with me. I have Dr. Chen from Stanford, Dr. Thai from Brown, and a couple of visiting scholars from The People's Republic of China, and Dr. Ying from Stanford working on this with me. So with our non-linear curve-fitting program we were able to come up with the eigenvalues and eigenvectors.

I will go over briefly what those are in a few minutes, but let me give you an overall picture first. Now, once you have the system eigenvalues, eigenvectors, then we continue from there. At this point let me go through the time domain roughly, because we're going to end up at the same place.

With the time domain, again, you look at the structure response, for instance, of an offshore platform or whatever you have under your environmental-type of excitation. Then you perform a random decrement analysis on it and you obtain the random decrement signatures.

Now, as I'll explain again a little bit later, with just the random decrement signatures you're only able to get the eigenvalues.

It would not give you the mode shapes. So we perform, at this stage, a cross-random decrement to obtain the signatures that, in turn, will give us the eigenvectors.

So essentially through both the frequency domain and the time domain, we're able to obtain the eigenvalues and the eigenvectors.

From there we use the system identification techniques and, knowing the residues with eigenvalues and eigenvectors, we are able to come up with the mass stiffness and the damping matrices in the state equation form. That's another point where there is some confusion because most people stop at the point where we get the eigenvalues and eigenvectors. We go a step further and obtain the actual mathematical model in the state equation form with the mass, stiffness, and damping matrices.

T^at's essentially what the system identification is. We go through a structure that doesn't have any damage, and go through these techniques. Now, for those structures that have clearcut inputs, we can go through the frequency domain and for those under random excitation where it's very difficult to measure the input, we go through the time domain technique and we can come up with mass, stiffness and damping matrices. Then if we repeat the process for a case where we have some damage in the structure, we go through the process and we come up with maybe different mass, stiffness and damping matrices.

And hopefully by identifying the various terms we might be able to relate it to a particular location. That's what we're hoping to work on.

Figure 4. I just want to go roughly through a couple of things, one method in the frequency domain with cross-random dec. If you want details of these, we haven't published anything yet.

For the non-linear curve-fitting method which we use, essentially you start off with the system's complex frequency response function -- F (   ) = F~1\ (   ) + iF~2\ (   ). F~1\ and F~2\ are the real and imaginery parts of the system frequency response. The spectral curve is curve-fitted. So essentially what we do is pick a penalty function and minimize it.

We have another professor working with us from the Electrical Engineering Department in Controls, so we could use some very nice optimization type of programs. I think the controls people in the electric engineering department and the vibration people, after awhile, come very, very close together and one could help the other tremendously.

NON-LINEAR CURVE FITTING

THE SYSTEM'S COMPLEX FREQUENCY RESPONSE FUNCTION

$$F(\omega) = f_1(\omega) + i\, f_2(\omega)$$

IS CURVE FITTED BY THE THEORETICAL EXPRESSION

$$G(s) = \sum_{k=M}^{M} \frac{A_k}{S - P_k} \qquad (1)$$

MINIMIZE THE PENALTY FUNCTION

$$\delta^2 = \frac{1}{N} \sum_{i=1}^{N} \left[F(\omega_i) - G(\omega_i)\right]\left[F^*(\omega_i) - G^*(\omega_i)\right] \qquad (2)$$

WHERE: $f_1(\omega) \equiv$ REAL PART OF SYSTEM'S FREQUENCY RESPONSE

$f_2(\omega) \equiv$ IMAGINARY " " " "

$P_k \equiv$ SYSTEM'S EIGENVALUE

$A_k \equiv$ RESIDUE

Figure 4

It sounds very easy, but it takes a while to implement this particular technique. Again, you do not curve-fit one mode at a time. Theoretically this technique can curve-fit any number of modes -- whatever curves you have on the frequency response curve, the spectrum curve, you can just curve-fit that.

Those who are very familiar with this type of analysis, might not need me to explain, but essentially what we're getting from this non-linear curve-fitting program are the system eigenvalues -- the residues, which essentially are the product of the eigenvectors.

Also from this technique you get the eigenvalue and the eigenvectors.

Figure 5 discusses the auto-regression method with random dec. Essentially, with this auto-regression method, we can write the random decrement signature in discrete time series.

It's impossible to explain this whole technique in a relatively short time, so I'll just point out the important things. Many papers have been written on auto-regression techniques, I just want to point out how we use it with respect to random dec.

The eigenvalues can be obtained from finding the roots of this polynomial after going through the linear-regression technique to get these coefficients. From the roots of this polynomial equation, it would give you the eigenvalues.

Essentially the polynomial is in a form where Z can be written as e\TKW~ where TK is the eigenvalue. So essentially we can find from the auto-regression technique the system's eigenvalue.

Now if you want to go further and look at eigenvectors, now that you have the eigenvalues, you have a problem. For those that are familiar with random decrement signatures, essentially it's an averaging technique in which if you take the response of a structure under, say, random excitation, and you are able to get free response or the response to the impulse. With that, however, we normalize the initial displacement, so we do not have the phase information or what you call the eigenvectors just from looking at the random decrement signature.

AUTO-REGRESSION METHOD WITH RANDOMDEC

THE RANDOM DECREMENT SIGNATURE CAN BE WRITTEN AS THE FOLLOWING DISCRETE TIME SERIES

$$X(n\Delta t) = \sum_{k=1}^{M} \left[A_k e^{nP_k \Delta t} + A_k^* e^{nP_k^* \Delta t} \right] \qquad (3)$$

$$n = 1, 2, 3, \ldots N$$

SATISFYING THE LINEAR DIFFERENCE EQUATION OF ORDER $2M$,

$$X(n\Delta t) = \sum_{i=1}^{2M} S_i X((n-i)\Delta t), \quad n = 2M+1, \cdots, N \qquad (4)$$

THE LINEAR REGRESSION METHOD IS USED TO SOLVE S_i FROM (4).

THE ROOTS, $Z_k \equiv e^{P_k \Delta t}$, OF THE FOLLOWING POLYNOMIAL EQ.

$$Z^{2M} - S_1 Z^{2M-1} - S_2 Z^{2M-2} - \cdots - S_{2M} = 0$$

GIVES THE SYSTEM'S EIGENVALUE

$$P_k = \ln Z_k / \Delta t$$

THE EIGENVECTORS ARE FOUND FROM EQ. (3) USING THE LINEAR-LEAST-SQUARE FIT.

However, we can use the so-called "cross-random decrement technique" to get this information.

Figure 6 shows the difference between a random decrement signature and a cross-random decrement signature. In a random decrement signature we select a threshold level -- on the time response curve, and by signaling processing, you're able to come up with a free vibration decay curve.

We get a random decrement signature -- for every transducer that we have. However with a cross-random decrement signature similar to, for instance, the concept of acoustic emission techniques where you use more than one sensor, and you use triangulation to try to help you, the cross-random dec is utilized if you have more than one sensor and you get the time response simultaneously. In the cross-random dec we elect a threshold in the first signature and, we let that be the starting point for intervals in the time response curve on the next sensor.

Select our segments that way and we average them rather than just do a straight random decrement analysis on each sensor. So this way we're able to get a cross-type of correlation between the various sensors.

Figure 7 demonstrates that once you have the eigenvalues and eigenvectors, the system identification technique we have developed essentially obtains the mass, stiffness, and damping matrices. It takes a little longer than just saying that, but with the eigenvalues and eigenvectors we can come up with the mass, stiffness, damping matrices. That's important.

Now we did a number of things. First of all we wanted to build up confidence in ourselves in that whatever we developed was usable, so that first we tried many theoretical cases. Then we wrote a FORTRAN program and applied loading to it, and got the response. We came up with mass, stiffness, and damping matrices for both cases to see if it was the same. It worked, of course.

First of all, there's no noise. For those of you that work in controls or with running these algorithms, one of the most difficult problems is how to get rid of the noise you get in the real system.

However, as an exercise, we went through the theoretical cases -- and I just want to show you one quick result of another exercise where we had a cantilever beam in which we applied different types of loading.

CROSS RANDOM DECREMENT

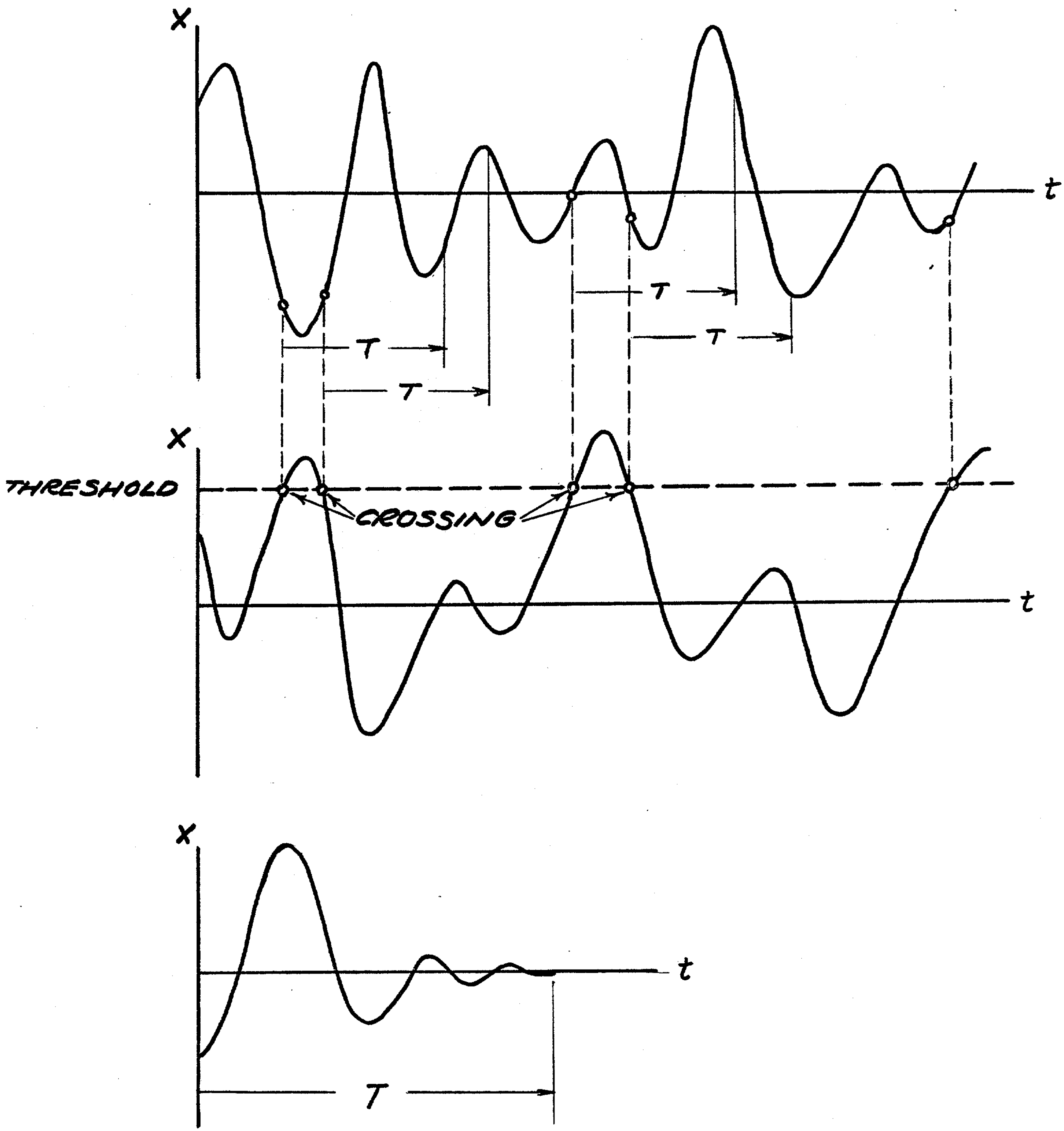


Figure 6

THE SYSTEM IDENTIFICATION TECHNIQUE

THE STRUCTURE IS DESCRIBED BY THE DYNAMIC EQUATION

$$[M]\{\ddot{x}(t)\} + [C]\{\dot{x}(t)\} + [K]\{x(t)\} = \{f(t)\} \qquad (5)$$

USING STATE-EQUATION FORMULATION, EQ. (5) BECOMES

$$\left[\begin{array}{c:c} [0] & [M] \\ \hdashline [M] & [C] \end{array}\right] \left[\begin{array}{c} \ddot{X}(t) \\ \hdashline \dot{X}(t) \end{array}\right] + \left[\begin{array}{c:c} -[M] & [0] \\ \hdashline [0] & [M] \end{array}\right] \left[\begin{array}{c} \dot{X}(t) \\ \hdashline X(t) \end{array}\right] = \left[\begin{array}{c} 0 \\ \hdashline f(t) \end{array}\right] \qquad (6)$$

DEFINING $\equiv$

$$[D] = \left[\begin{array}{c:c} [0] & [M] \\ \hdashline [M] & [C] \end{array}\right], \qquad [E] = \left[\begin{array}{c:c} -[M] & [0] \\ \hdashline [0] & [K] \end{array}\right]$$

IT CAN BE SHOWN:

$$[D] = [Y]^{-1^T}[I][Y]^{-1}, \qquad [E] = [Y]^{-1^T}[-P][Y]^{-1}$$

WHERE THE TRANSFORMATION MATRIX $[Y] = [\{Y_1\} \vdots \{Y_2\} \vdots \cdots \vdots \{Y_{2m}\}]$ IS THE COLUMN VECTORS OF THE SYSTEM'S $2m$ EIGENVECTORS $\{Y_K\}$

$$[P] = \begin{bmatrix} P_1 & & 0 \\ & P_2 \ddots & \\ 0 & & P_{2m} \end{bmatrix}$$ IS THE DIAGONAL EIGENVALUE MATRIX

Figure 7

You put, say, six accelerometers on this thing. Then one way of exciting it is just impact it with a hammer, so you know what the input is. And then we go through this exercise and we're able to come up with the mass, stiffness, and damping matrices -- the actual matrices.

This is a real problem. It is much simpler than an offshore platform, of course, at least at the start, because it is a continuous beam and not a lumped mass system.

After we got the mass, stiffness and damping matrices, to gain a degree of confidence that these values are actually close to the right values, we went ahead and used a mathematical model.

We are able to get the eigenvalues and eigenvectors. As shown in Figure 8, we only looked at four accelerometers. So this is a 4 degree of freedom system.

Figure 9 shows the type of mass, stiffness, and damping matrices that you get. This is not exact, but we don't have an exact system. You can't represent the beam as a continuous beam. However, we want to check. How good are these results? So we look at the results both from the experimental data and then look at the results from the mathematical model we have obtained and see if we get the same thing.

In Figure 10 for instance, this is the data measure at the first station, at the sixth station, different positions of the accelerometer. This is a transfer function from the original experimental data.

Figure 11 is from using the mathematical model. I have many more of these curves if you would like to see. Essentially, to continue this research, we would like to look at a little bit more than just the offshore platform, -- maybe some plate structures and other types of structures as well. So we are looking at now -- in Figure 12 -- for instance, a composite beam, three layers and so on.

We want to try a couple of simple configurations first. By the way, we went through the cantilever beam with a crack. We noticed a change in the mass, damping, and stiffening matrices. Those are going to be written up and published in a report.

But what we hope to continue to do from here is take a composite beam, look at the lamination, look at cuts in the

CANTILEVER BEAM

MODE	FREQ. HZ	DAMP. %	RESIDUES							
			STATION #1		STATION #2		STATION #4		STATION #6	
			REAL	IMAG.	REAL	IMAG.	REAL	IMAG.	REAL	IMAG.
FIRST	26.08	5.000	.0259	.00939	.0445	.0166	.284	.0849	.276	.0727
SECOND	161.03	1.585	-.189	-.0119	-.232	-.0226	-.335	-.0207	.314	.0373
THIRD	456.70	0.678	.321	.00674	.238	.0162	-.365	.116	.275	-.00476
FOURTH	885.45	0.600	-.469	-.0000474	-.0625	-.00827	-.0855	.049	.262	.0114

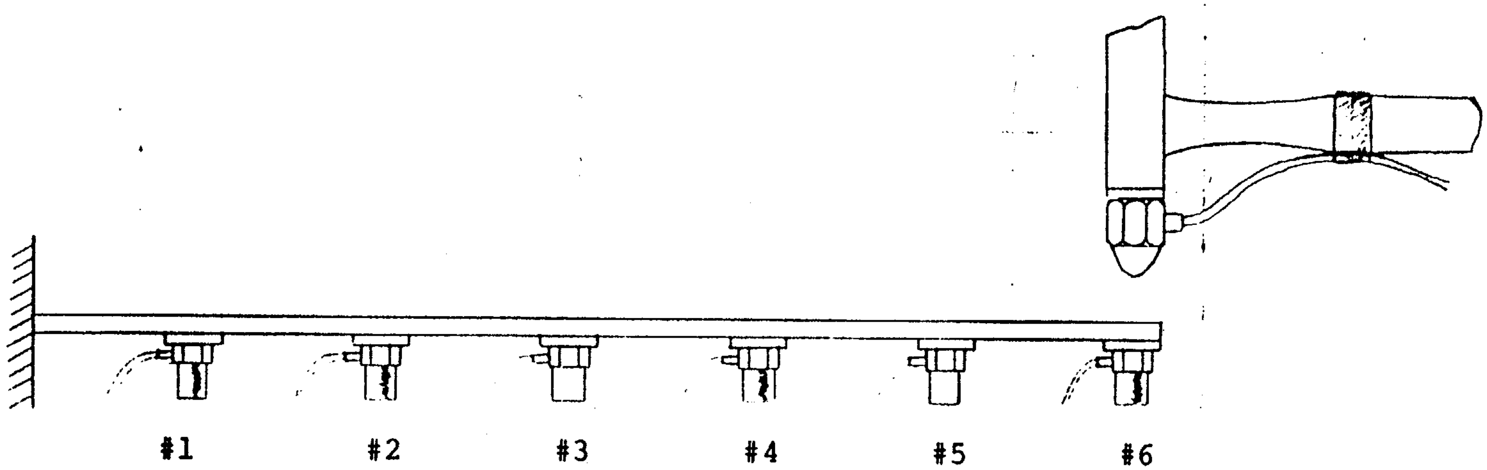


Figure 8

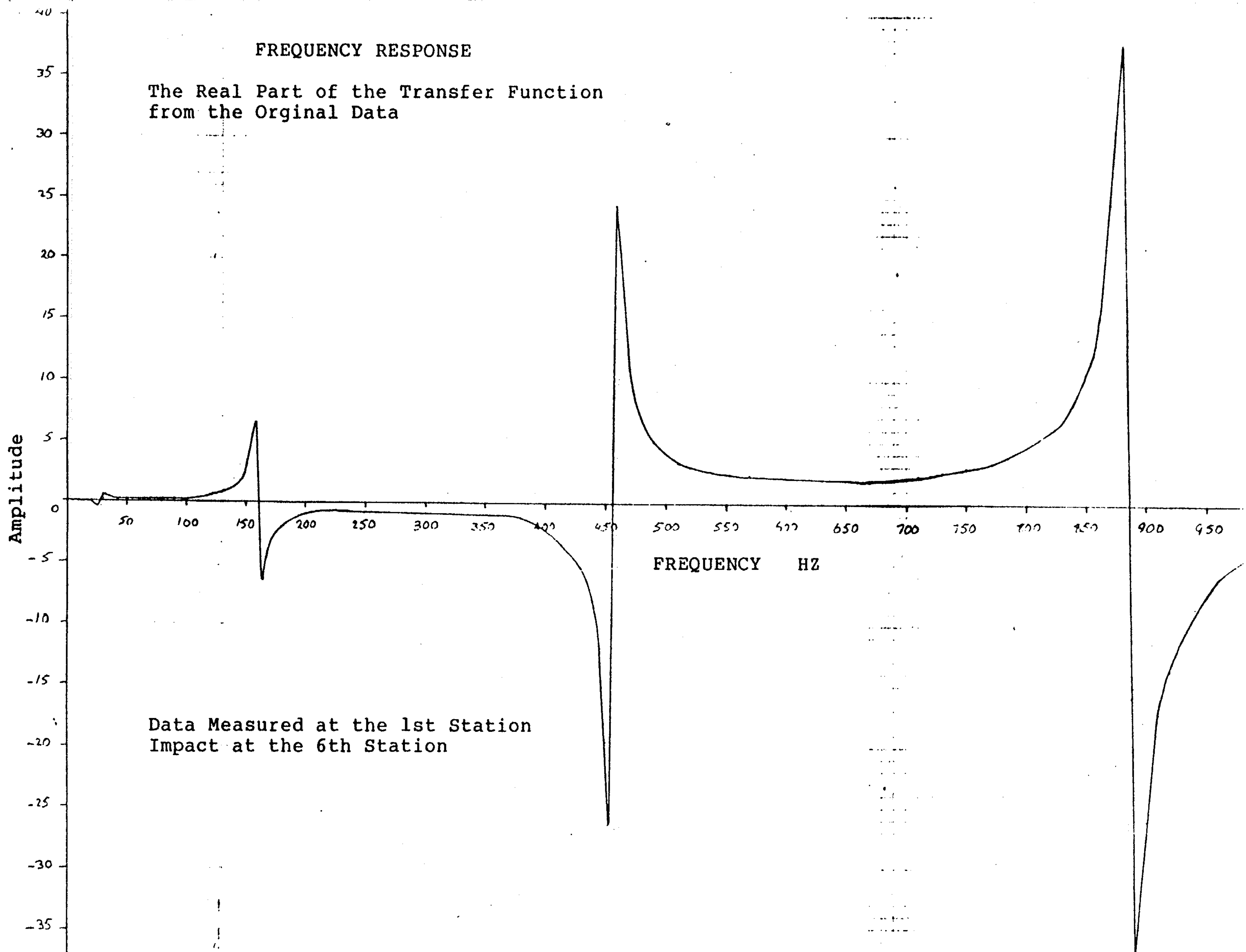
MASS [M], DAMPING [C], and STIFFNESS [K] MATRICES

$$[M] = \begin{bmatrix} 1.135 & -1.596 & 0.248 & 0.268 \\ -1.363 & 3.056 & -0.237 & -0.404 \\ 0.533 & -0.945 & 0.728 & 0.130 \\ 0.753 & -1.254 & 0.500 & 0.483 \end{bmatrix}$$

$$[C] = \begin{bmatrix} -9.56+02 & 1.45+03 & -5.67+02 & -1.22+02 \\ 1.45+03 & -1.88+03 & 1.05+03 & 1.73+02 \\ -5.67+02 & -1.05+03 & -4.54+02 & 8.82+01 \\ -1.22+02 & 1.73+02 & 8.82+01 & 1.33+02 \end{bmatrix}$$

$$[K] = \begin{bmatrix} 2.16+07 & -2.26+07 & 2.31+06 & -7.04+05 \\ -2.26+07 & 2.88+07 & -4.23+06 & 1.71+06 \\ 2.31+06 & -4.23+06 & 1.19+06 & -7.30+05 \\ -7.04+05 & 1.17+06 & -7.30+05 & 5.57+05 \end{bmatrix}$$

Figure 9


FREQUENCY RESPONSE
The Real Part of the Transfer Function
from the Orginal Data
Data Measured at the 1st Station
Impact at the 6th Station
Amplitude
FREQUENCY HZ
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
40
35
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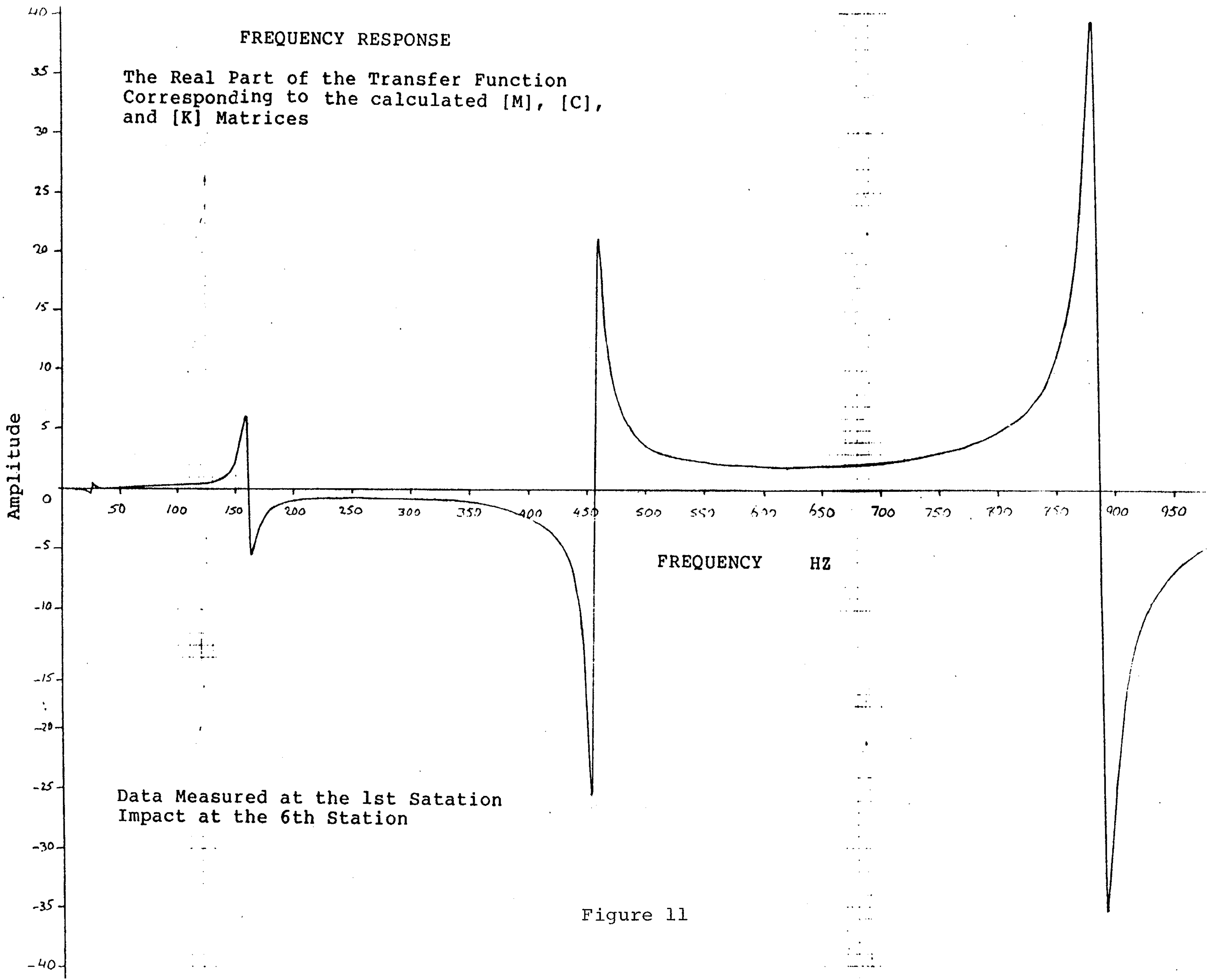
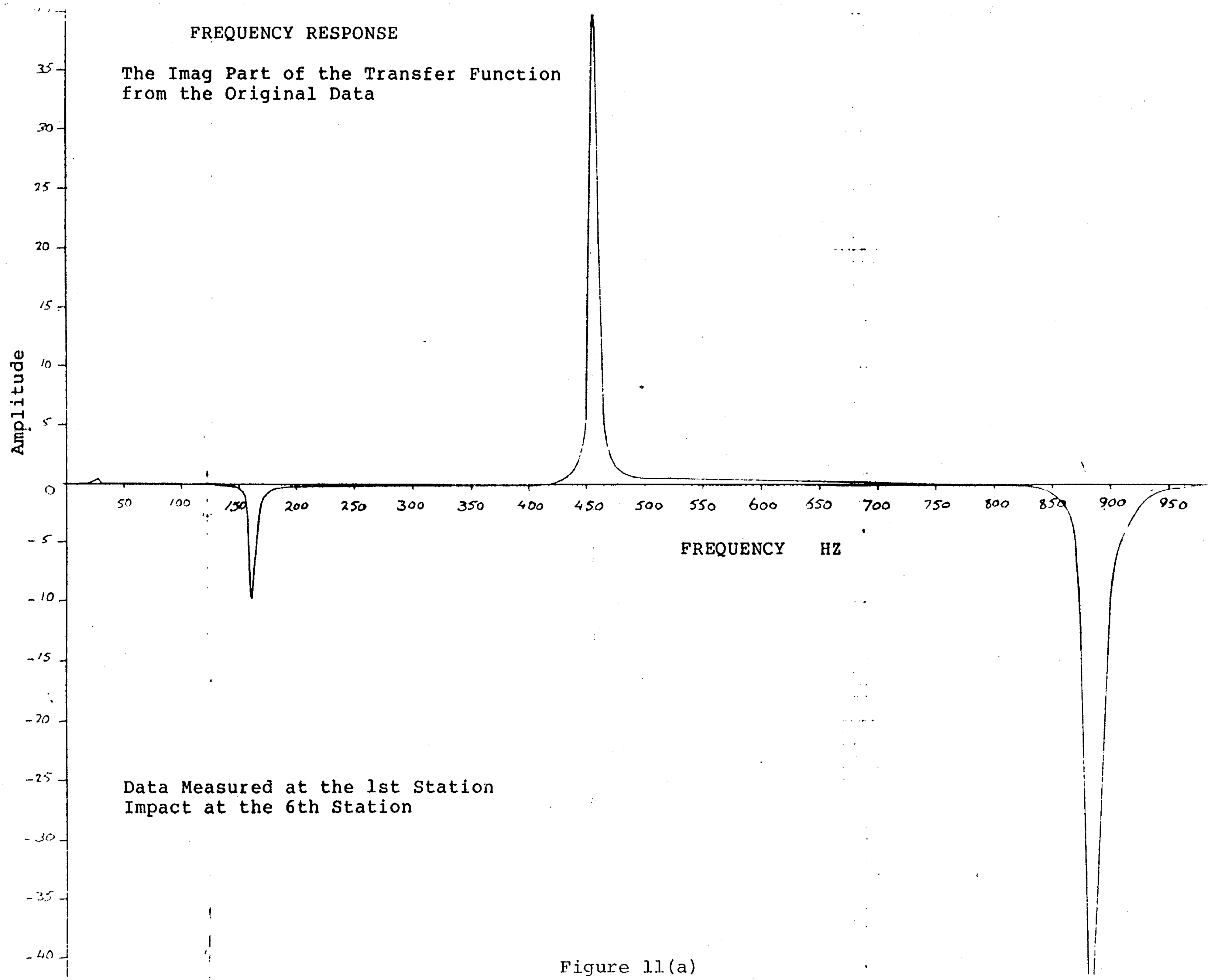
-20
-25
-30
-35

Figure 10



FREQUENCY RESPONSE
The Real Part of the Transfer Function
Corresponding to the calculated [M], [C],
and [K] Matrices
Amplitude
FREQUENCY HZ
Data Measured at the 1st Satation
Impact at the 6th Station

Figure 11


FREQUENCY RESPONSE
The Imag Part of the Transfer Function
from the Original Data
Data Measured at the 1st Station
Impact at the 6th Station
Amplitude
35
30
25
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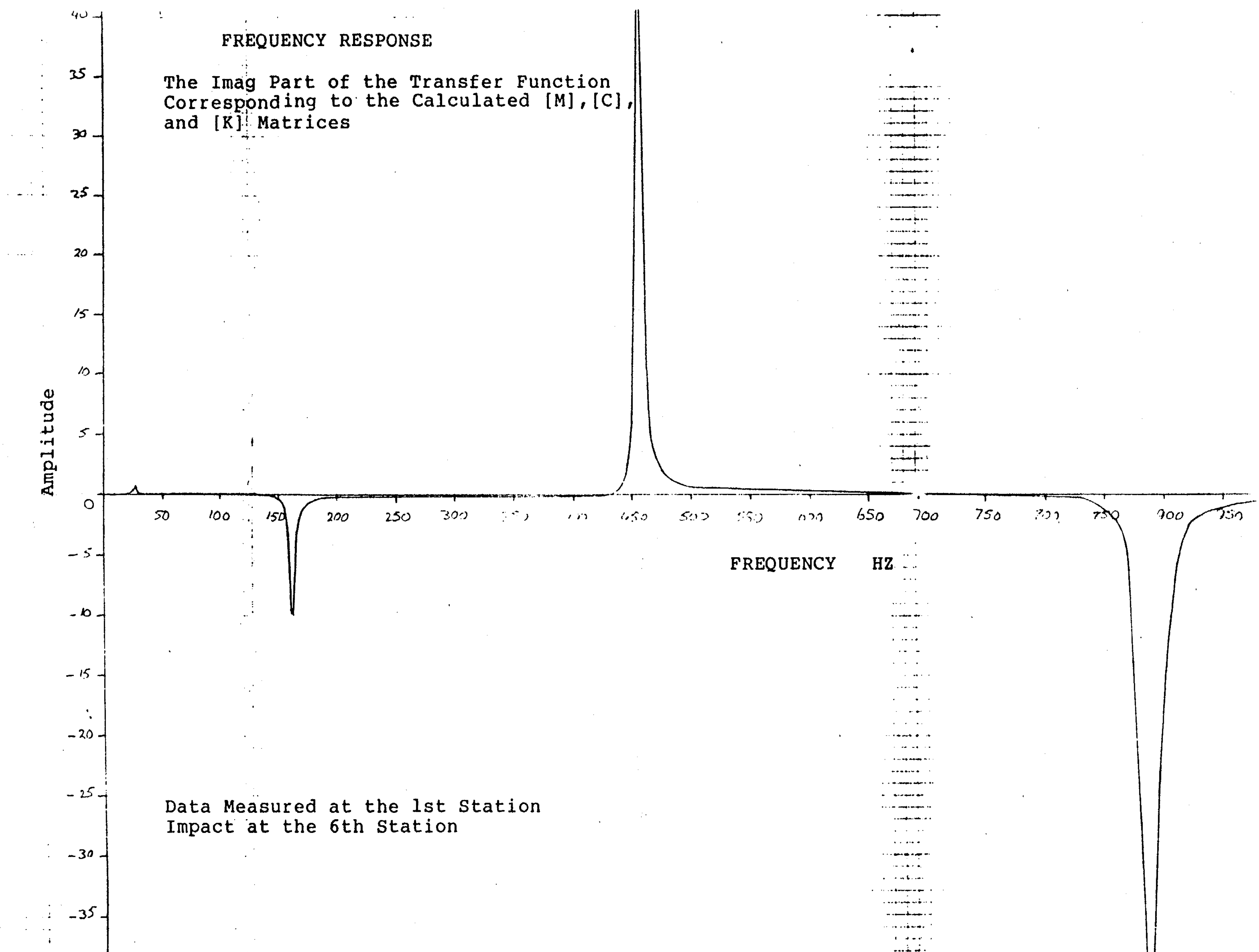
700
750
800
850
900
950
FREQUENCY HZ

Figure 11(a)



FREQUENCY RESPONSE
The Imag Part of the Transfer Function
Corresponding to the Calculated [M],[C],
and [K] Matrices
Data Measured at the 1st Station
Impact at the 6th Station
Amplitude
FREQUENCY HZ

Figure 11(b)

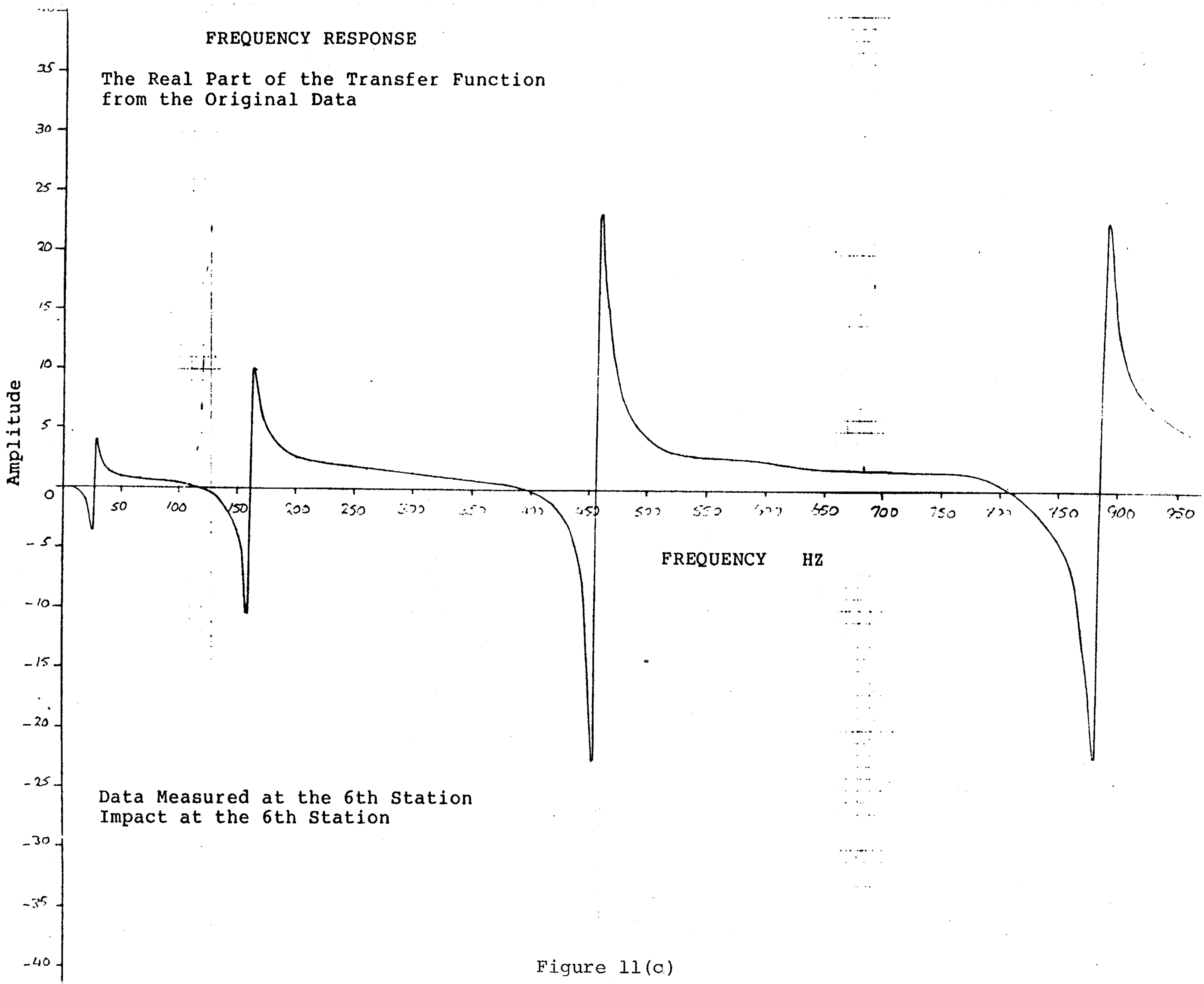

FREQUENCY RESPONSE
The Real Part of the Transfer Function
from the Original Data
Amplitude
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
50
100
150
250
650
700
900
950
FREQUENCY HZ
Data Measured at the 6th Station
Impact at the 6th Station

Figure 11(c)

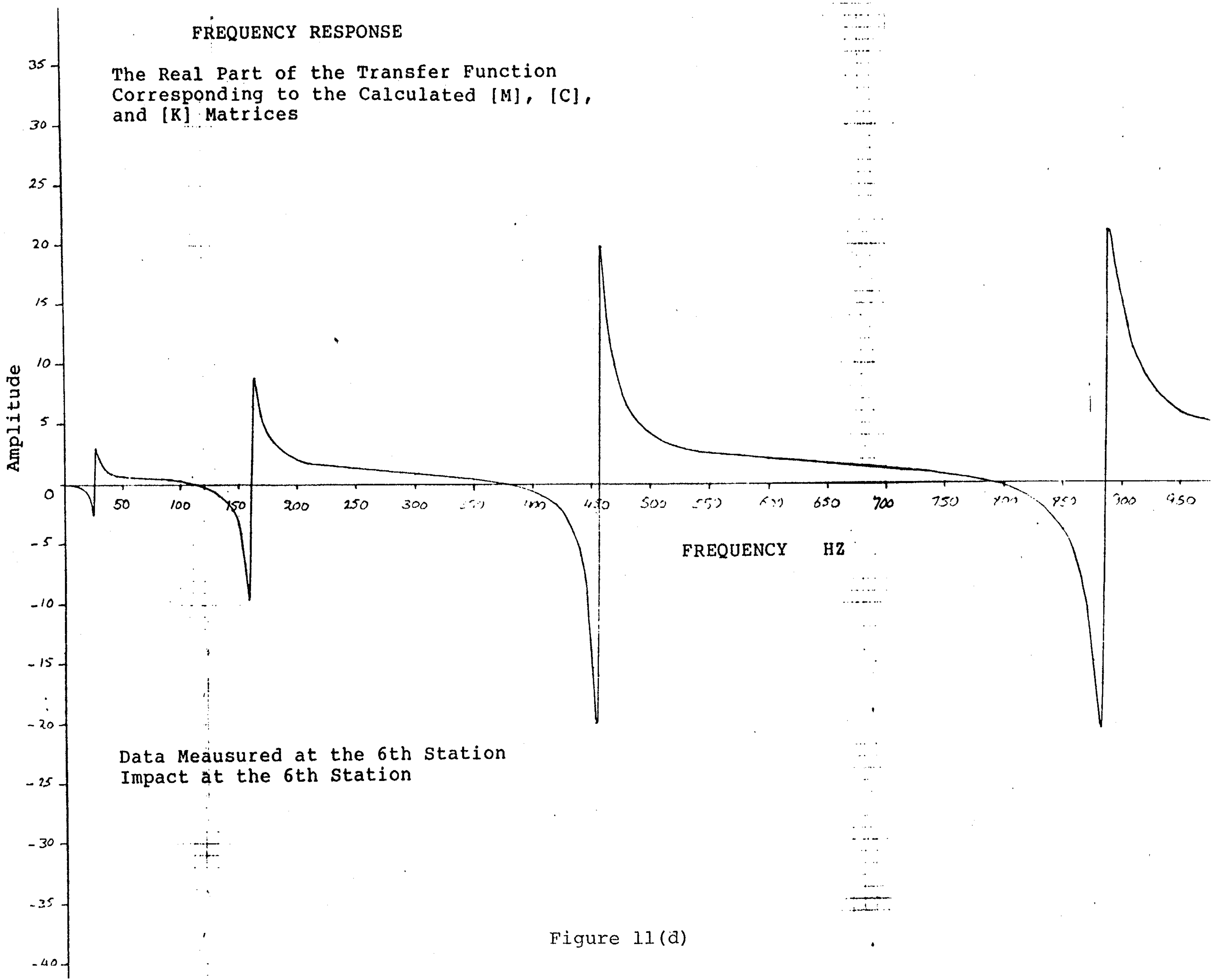

FREQUENCY RESPONSE
The Real Part of the Transfer Function
Corresponding to the Calculated [M], [C],
and [K] Matrices
Amplitude
35
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
50
100
150
200
250
300
450
500
650
700
750
FREQUENCY HZ
Data Meausured at the 6th Station
Impact at the 6th Station

Figure 11(d)

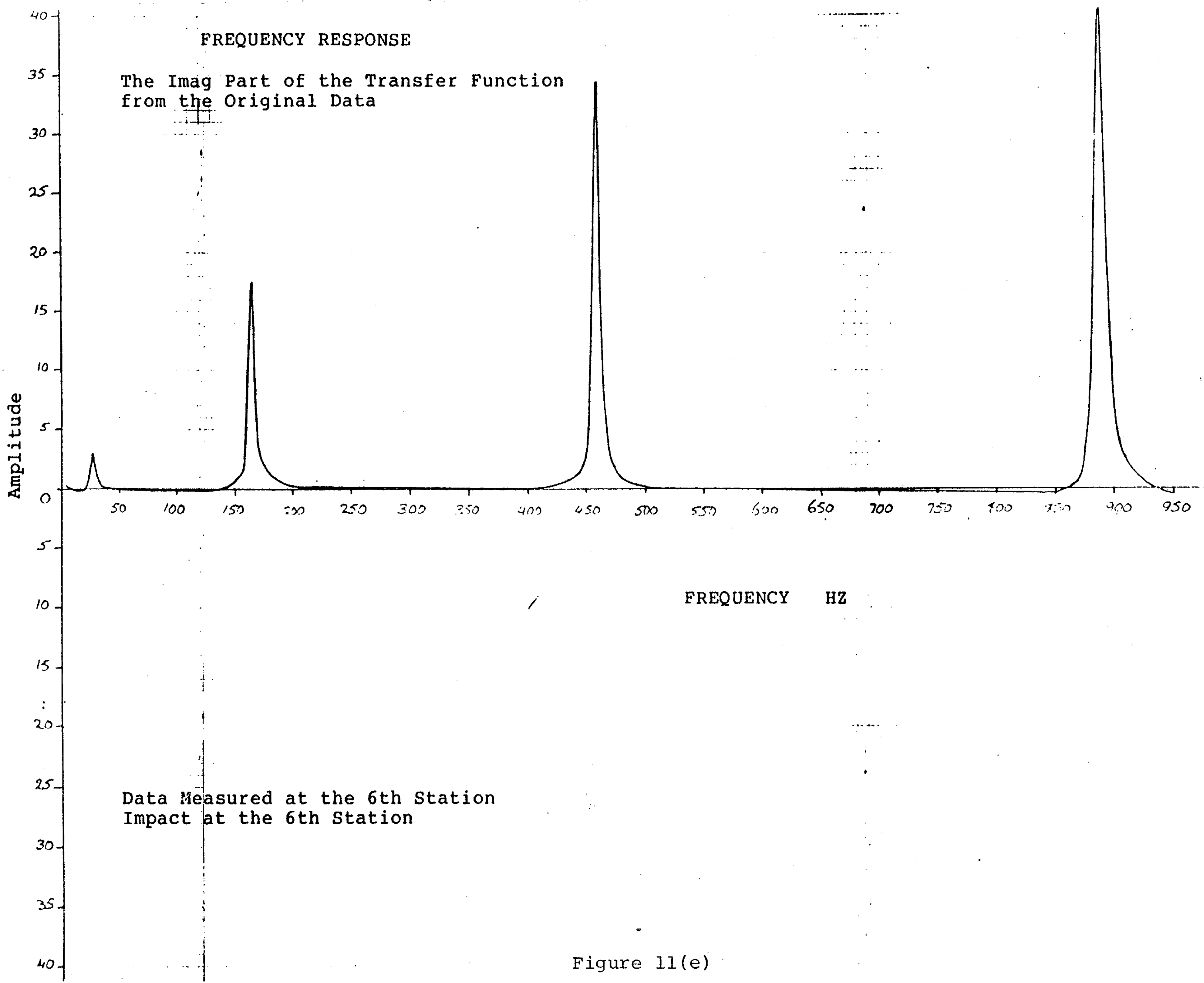

FREQUENCY RESPONSE
The Imag Part of the Transfer Function
from the Original Data
Amplitude
FREQUENCY HZ
Data Measured at the 6th Station
Impact at the 6th Station

Figure 11(e)

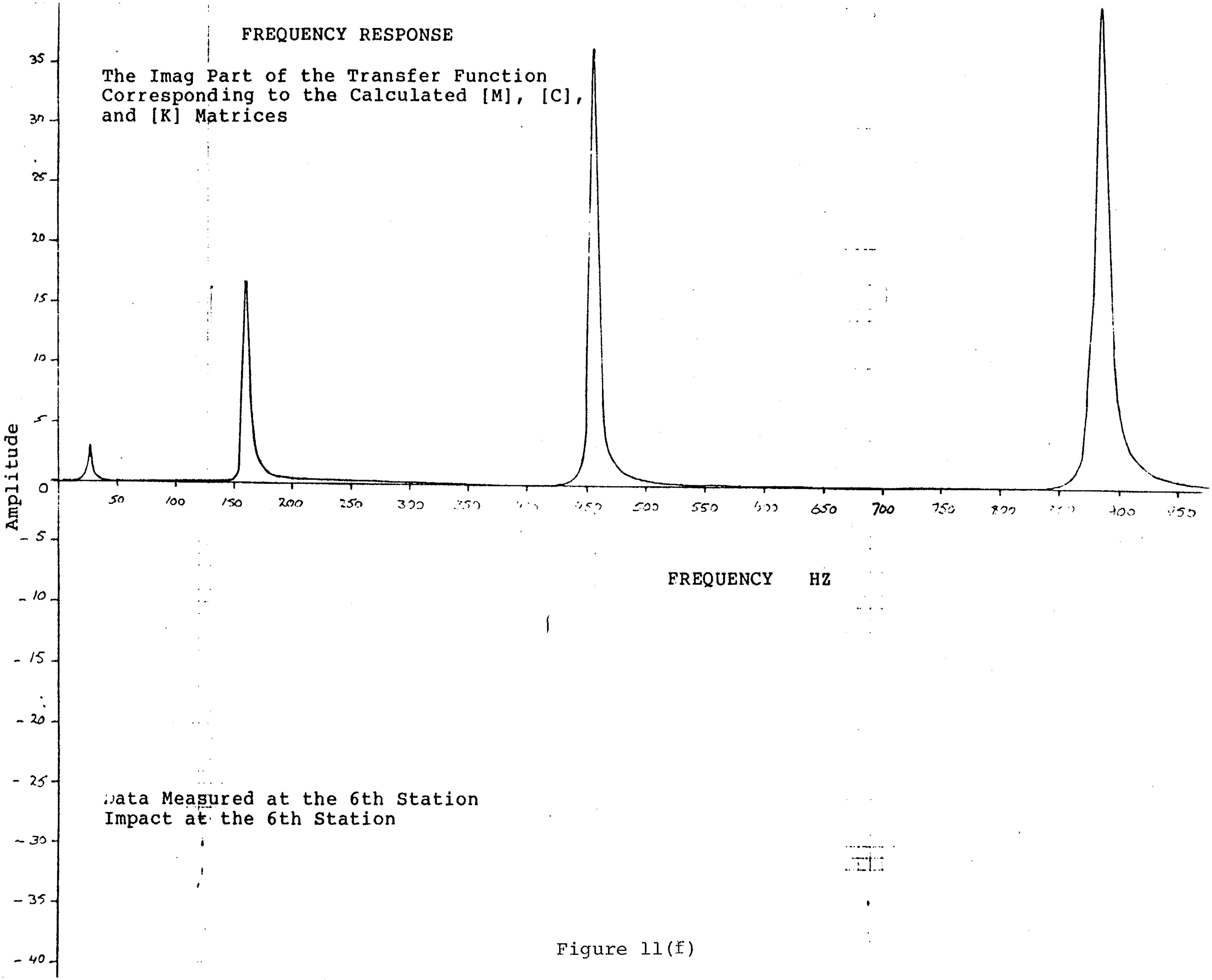
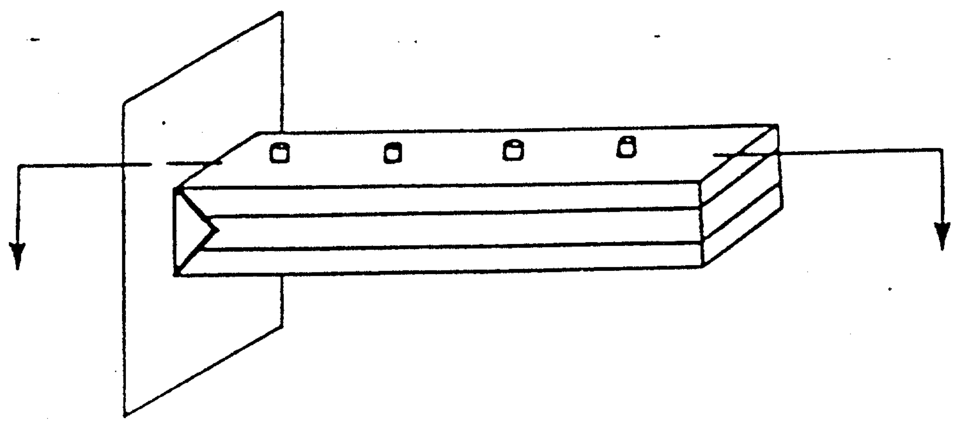
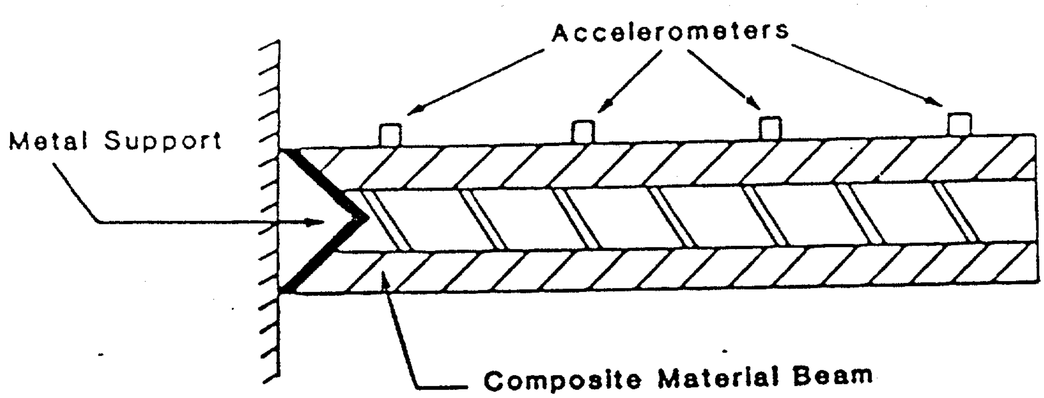

FREQUENCY RESPONSE
The Imag Part of the Transfer Function
Corresponding to the Calculated [M], [C],
and [K] Matrices
Amplitude
FREQUENCY HZ
Data Measured at the 6th Station
Impact at the 6th Station

Figure 11(f)





A–A View

Figure 12

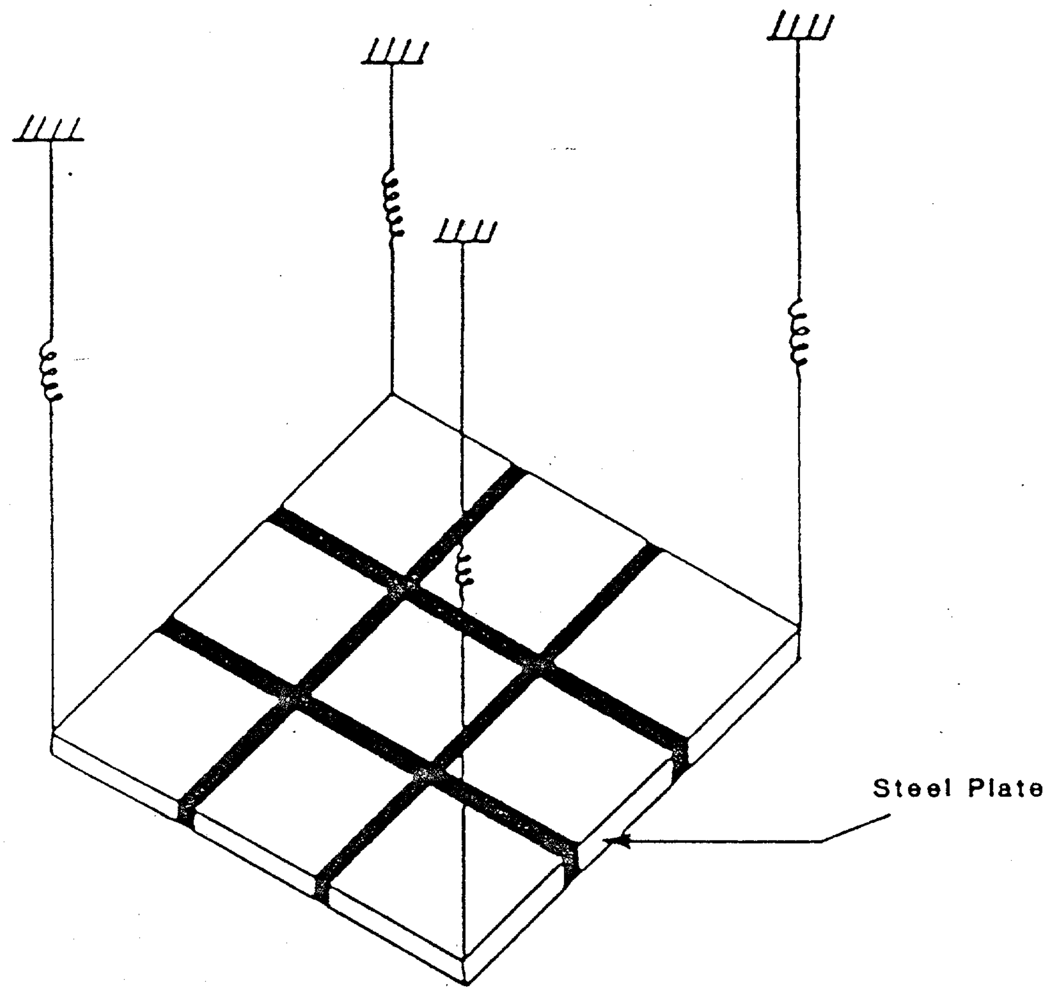


Figure 13

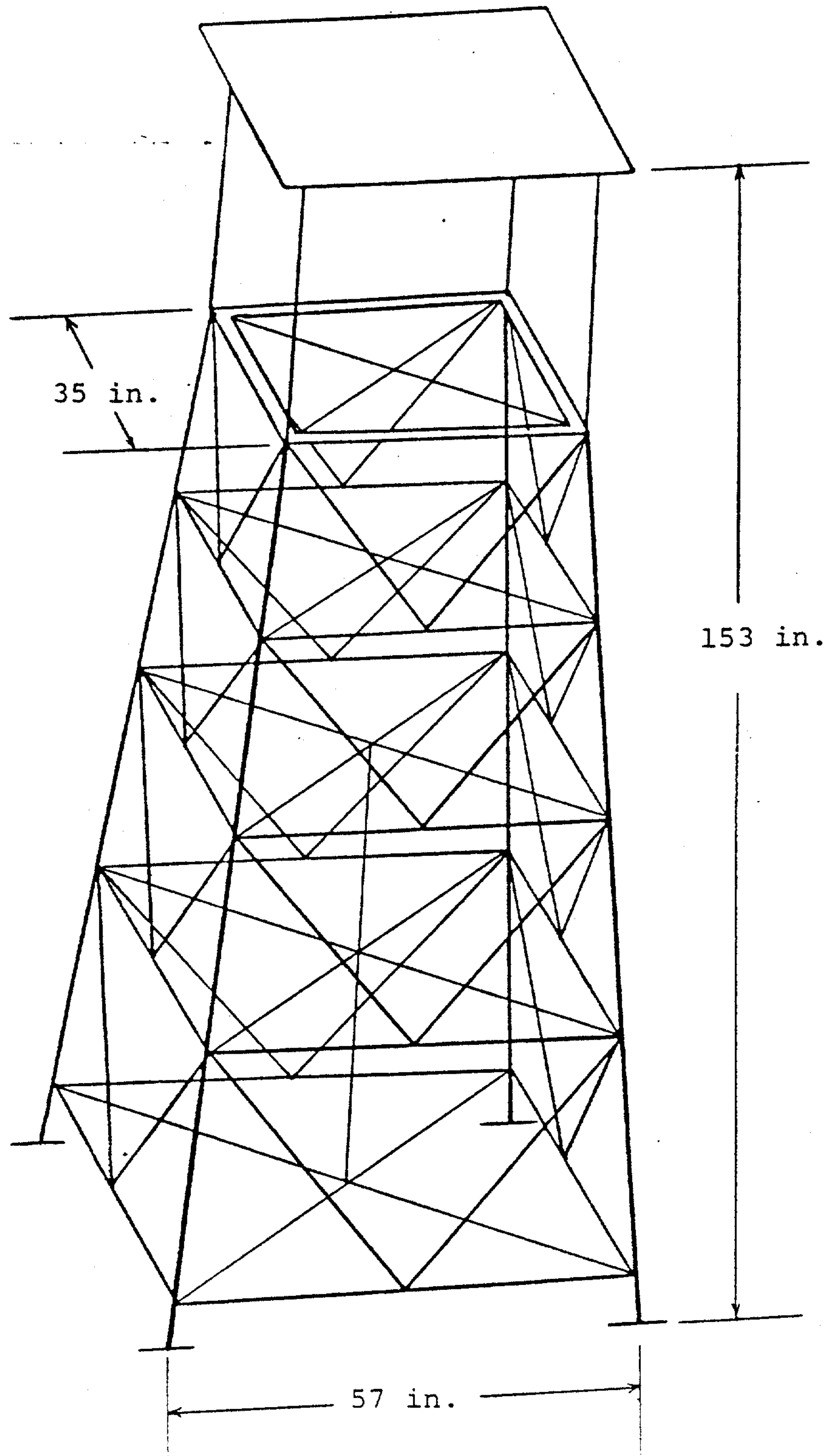


Figure 14

beam, and every time we put some damage to it we would go through the system identification technique, whether in the frequency domain or time domain -- in the time domain, if we don't know the input in the frequency domain.

If we do a nice control test, we will come up with the mass, stiffness, and damping matrices in the mathematical model and watch for changes.

So this is the composite beam. For those in NASA these don't look like any real problems either, but that is a start.

You have got to build up your confidence somewhere. A technique is a technique.

Figure 13 shows a plate, for instance, that is welded. We are going to put cracks at the welds in various positions, and hope that from the cross random dec technique and system identification we are able to identify the locations of the cracks.

We built a twin reverberating chamber at Maryland eight or nine years ago in which we would just like to try putting the plate in between the walls of this twin reverberation chamber. We are going to blast it with a loudspeaker, and that is it.

Then we will see if we can get the mathematical model of the plate without, and then with, the cracks.

Figure 14 is the offshore platform, which is a much more complex structure, but we are working on this also. We are banging this at various places and looking at the responses and hoping to come up with, also, a mathematical model much more complex than the others.

Nevertheless, we will attempt to see if through this technique, by looking at more than one sensor, we come up with a technique that can possibly locate the defect.

DR. GORDON: Al Gordon from NASA. I just wonder how you go from this system of stiffness and damping matrices to a picture of what the system is.

DR. YANG: That is the difficult part. We are learning right now to see how we can relate the real structure to the various terms in the mass matrix and the stiffness matrix and the damping matrix.

There is no problem if you have one mass, but this is one area we are looking at quite a bit.

First, though, we must look at the technique, get the mass, stiffness, and damping matrices. That is the first step. That took a long time.

Just seeing these viewgraphs doesn't indicate the amount of time that was spent in writing the algorithm and researching where it converges.

But you are absolutely right, we haven't got there yet. We are working on that right now.

MR. BOLELHO: Did you apply the technique to linear systems as well?

DR. YANG: We first worked on the mass, stiffness, and damping matrices -- and once we have this thing solved -- and this is by no means solved, we would like to see this actually work on real structures.

It works on beams. We just finished a problem on projectiles which was very nice, yet a different configuration. But we have not really gone further.

DR. BASDEKAS: Can you share with us your confidence that by observing a macro scale response you might be able to determine cracks on the micro scale? Do you have any indication that somebody managed to do that?

DR. YANG: The question is what size of crack.

DR. BASDEKAS: We are observing the length, you know, and the crack is 1/10,000ths lengthwise. It is a different length scale. You have a macro observation to end up with a determination on the micro scale.

DR. YANG: We cannot really give you a definite number, saying that we get this type of crack on this side, this distance away. This is problem dependent.

We have though, a number of papers published with ASME at Chicago and ASME at San Francisco, in which we have actually observed a small model of a platform where we detected cracks of 1/16th of an inch that is 3 feet away.

Also, we have detected cracks, with the help of Hank Cole at the SME nuclear conference back in San Francisco about five or six year ago. They were also of that length, about 1/16th of an inch, at about 5 feet away.

DR. BASDEKAS: Whatever you did observe, you measured something. How did you uniquely more or less solve the problem to tell you where is the crack and what is the size of it?

DR. YANG: As I indicated, we can only get an indication of the location. We don't know. That is why we are working on the problem now.

Hopefully, through looking at more than one transducer, we are able to do a cross random dec with system identification and possibly work towards finding the exact location, similar to triangulation and other techniques of trying to find the location of the crack. But right now we don't.

We will be looking at more than one sensor. Suppose we have four sensors. We cross this, cross that, in whatever combination. Then you observe different changes.

DR. BASDEKAS: Changes in what?

DR. YANG: In the signatures. The cross random dec signatures.

So from these changes, for instance, if there are more changes along here than here, most likely the crack occurs along this face.

DR. BASDEKAS: Can you differentiate between a crack and an increase in mass? What criterion are you using to differentiate between the reduction of stiffness or an increase of mass?

DR. YANG: This is always a difficult problem. I think Dr. Rubin also pointed out that sometimes by adding mass and doing something else, you could cause the same change.

The same thing with us. However, with random decrement, through some laboratory testing, there is some possibility of distinguishing different types of damages, for the reason that we are able to look at different frequency ranges for changes.

Certain types of damages will affect the fundamental frequency as well as other frequencies.

However, if you have a very small crack, it will only affect the higher frequencies, and gradually the low frequencies as the crack increases in size.

Again, this is very rough. So therefore, just in that specific example, if you were to try to distinguish between these two damages, you look at your random dec and you have the flexibility of looking at more than one frequency range. First, I'd look at the high frequency range. In one case I wouldn't see a change. In the other case, I see changes. Then I look at the low frequency range. One case you see a change. The other case you don't see a change.

Therefore, possibly from that type of analysis you are able to come up with some conclusions as to what are the differences in the types of damages.

DR. BASDEKAS: Right now is this speculation?

DR. YANG: No. I don't think I can pinpoint it, but at the same time it is not a speculation, because we have a total difference between a crack and, for instance, the lifting of a leg.

VOICE: I think Dr. Basdekas was talking about the system identification method.

In the system identification method, how are you going to find out if there is a crack?

He is right in pointing out that we are going to use a stiffness matrix in finding out what element changes most, to detect where the crack is.

DR. PERRONE: Specifically, in the round robin exercise, where there were some small members half sawed through and it was discerned that there was a change, what was the frequency range? What was the order of magnitude of that frequency range of the random dec signature that was referred to?

I assume those are higher frequencies.

DR. YANG: That I don't remember, I am sorry, because this has been over a year or so ago.

MR. CAMPBELL: Brad Campbell, with Exxon Production Research. What kind of a criterion was used to select the number of poles in your model, and how sensitive were your models to that selection.

DR. YANG: The more measured data you have, the better off you are, because our technique of curve fitting can make as many poles as you can fit in it. If you take three measurements versus 10 measurements, you get a different result. I think the better accuracy the more measurements you have.

Usually, we try to plan it to take what is considered the more important points.

MR. CAMPBELL: Do you look at the spectrum and see how many resonant peaks you see and then select 2 M as your number of poles?

DR. YANG: I go through all of them. Say the fundamental modes were definitely well covered. Then suppose you have 20 modes. So we curvefit the 20 modes.

MR. CAMPBELL: You go over the entire frequency range, or can you isolate it to certain regions?

DR. YANG: You mean the zooming type of thing? Yes, right.

MR. CAMPBELL: There is extensive literature, I think. Professor Gersh at Hawaii developed a number of models. It turns out those models are very accurate representations of mass damping stiffness, whereas a simple autoregressive model is a crude approximation that gets you reasonable results within a peak; but it is still a very crude process.

DR. YANG: I don't know about that work.

DR. SUNDER: This has to do with identifiability of mass, stiffness, and damping matrices from a limited number of modes for which you have measurements.

I recently happened to read a doctoral thesis by Dr. Peck at Cal Tech where he considered the definability issue in significant detail from a methematical point of view and found that for the earthquake problem that one could only derive uniquely the information on natural frequency, mode shape value, and the participation factor and the damping. But he sort of concluded that it might not be possible to get the unique calculation of the mass, stiffness, and damping matrices.

Would you care to comment on that?

DR. YANG: I do not know his work. This is, I presume, in civil engineering?

MR. BOLELHO: Earthquake engineering. Apparently, the people at Cal Tech are striving to come up with some more linear system representations.

DR. YANG: Right. Especially when the soil systems are highly nonlinear.

System identification has been worked on by many different people and each one has his contributions. There are a couple of places, as I have pointed out, where we are making a contribution, and this is an area we are going to concentrate on.

As far as uniqueness, right now for the technique we are using, at every step we are checking, in the sense that we try it out to see if we can get back what we started off with.

DR. SUNDER: I couldn't quite understand the distinction that you tried to derive between time and frequency domain, particularly since I view those as simple mappings of the same information. If I have a method that works without the knowledge of input in the case of time, it should be possible to do the same in frequency.

DR. YANG: I would like to know if anyone has come up with a mathematical model without knowing the input in the frequency domain?

DR. SUNDER: You are making a similar kind of assumption in the time domain.

DR. YANG: Right. Usually in the frequency domain type of problem you would use a hammer type of input to look at the situation whereas, in a real situation like an offshore platform, it would be difficult to apply that type of input to get you the information you want.

So we try to advocate the technique of random decrement. Every technique has its place, advantages, disadvantages. We always imply or advocate that the random decrement technique essentially is very good to be applied to a situation where you have an environmental type of excitation versus a prescribed type of excitation.

Peter M. Alea
NASA Goddard Space Flight Center

MR. ALEA: The random decrement is just one of the first techniques in which we are involved in at Goddard. There are other techniques, acoustic emission techniques, that might be of interest in the future.

The objective of the random decrement technique work at Goddard is as shown in Figure 1.

The purpose is to develop a technique for monitoring the structural integrity during environmental tests and for possible use in certifying the structure for reuse on the shuttle.

To elaborate, we are trying to evaluate a technique we can use during the qualification tests -- be it a vibration test or an acoustic test -- to tell the experimenter whether his experiment or flight hardware has experienced any type of structural degradation.

We are also trying to develop a technique that can be used for recertifying a payload after it is flown on the shuttle.

For instance, if a payload is initially tested in some type of vibration or acoustic test, and it flies on the shuttle and comes back down, we would like to be able to tell the experimenter with some degree of confidence that the structure is still sound.

We are trying to develop a technique to do that. Random decrement is the first technique we are looking at.

We at Goddard first became involved in the random decrement technique during the Round Robin program, (see Figure 2) held at Goddard and sponsored by the U.S. Geological Survey, now the Minerals Management Service, and the Office of Naval Research.

Our responsibility was as a support facility only. We provided the technicians to run the test as well as some engineering support to do the data processing. For the platform we provided that type of support, and for the K joint, basically we provided the technicians to run the equipment -- our equipment. That was the first fatigue test performed on the K joint, back in about November of 1980.

RDS OBJECTIVE

- THE PURPOSE OF THE RDS TECHNIQUE AT GSFC IS FOR USE IN DETECTING STRUCTURAL DEGRADATION DURING DYNAMIC ENVIRONMENTAL TEST AND FOR REFLIGHT ON SHUTTLE

Figure 1

ROUND ROBIN NDE PROGRAM

o SUPPORT FACILITY

1) OFFSHORE PLATFORM ROUND ROBIN TEST

2) FIRST K-JOINT FATIGUE TEST

o PARTICIPANTS

1) SECOND K-JOINT FATIGUE TEST

Figure 2

In August of last year, a second fatigue test was performed on the K joint. At that point we got involved, both as a support facility and as participants in the program, and the technique we were advocating was the random decrement technique.

(Slide) N/A

This is a slide of the 1/14 model of the offshore platform we tested. Basically what we did here is provide the engineering support for the data processing of the various accelerometers on the tower with Sheldon Rubin's technique; and we provided technician support for recording response data from the tower.

(Slide) N/A

There are a little over 50 accelerometers on the tower. Basically what we did is take those response accelerometers, batch them through some signal processing equipment, and perform various tests after that.

At this point all we did is provide technician support and some engineering to perform this test.

(Slide) N/A

Our next responsibility was a fatigue test on the K joint. This is about a one-third model of a true K joint.

We attached an actuator between the two legs of the joint, just like it would be in K joint fatigue. That was back in November of 1980.

VOICE: How did you load it?

MR. ALEA: A compressive and tensile load, sinusoidal loading. I don't remember now what the loading was, but it was in the neighborhood of a few hertz.

(Slide) N/A

In August of last year we performed fatigue tests on the remaining two sets of legs, which you can see in this setup here. In this series of tests, there were three different advocates. In the first series of tests, there was only one advocate, which was Drexel University's group.

In this case, there were three different advocates. The first, of course, was the acoustic emissions setup which you

MODE SELECTION

o SYSTEM MODES .VS. LOCAL MODES

1) NATURAL FREQUENCY

2) MODE SHAPE

Figure 3

see here, the Federal Highway Administration; the ultrasonic technique and our random decrement technique, which is off to the side here.

(Slide) N/A

Again, we did attach a hydraulic actuator between the two main legs of the K joint. The second K joint was cycled at about 1 1/2 hertz, about 1.6 hertz, to failure.

(Slide) N/A

For the random decrement technique, what we do is attach a mechanical exciter about the center of the main leg on the K joint.

We attached several response accelerometers to the two legs. In this case, we used five response accelerometers.

There were also some strain gages on the K joint, but we did not do any of the data analysis from the strain gages.

(Slide) N/A

This is the typical setup we used for the random decrement technique. We started out by selecting the various modes in which we were interested. We then shaped our forcing function to excite those modes to the desired level.

We record the response accelerometers on tape, and then the analysis is performed later on a computer.

(Slide) N/A

This is the K joint after failure. There are two main cracks that appeared at about 85,000 cycles in the joint.

In this fatigue test we only cycled the joint in a tensile mode. So we cycled the ram out and then back to the neutral position.

We used three accelerometers for doing this analysis. One was placed roughly in the center of the K joint. Two others were placed on this leg of the K joint. One was about 5 centimeters down from the weld, the second one about 50 centimeters down from the weld.

Those are the ones we performed the random decrement on.

(Slide) N/A

This is a closeup of the crack. There were two cracks. One was approximately 10-1/2 inches in length on the inside of the weld. The other was about 12-1/2 inches in length on the inside, and a smaller crack developed on the outside of the weld on the leg itself.

(Slide) N/A

As I said, the first step we performed is selection of the modes. There is, of course, a set of system modes that we looked at and a set of local modes.

Of course, the system modes are modes of the entire system -- the K joint, the A frame, and the whole assembly.

What we were interested in is the set of local modes, the local modes being only of those two legs. So we were interested in looking at the higher order local modes.

We first looked at the natural frequency, then the mode shape. From those two, we set our parameters from which we could extract the random decrement signature.

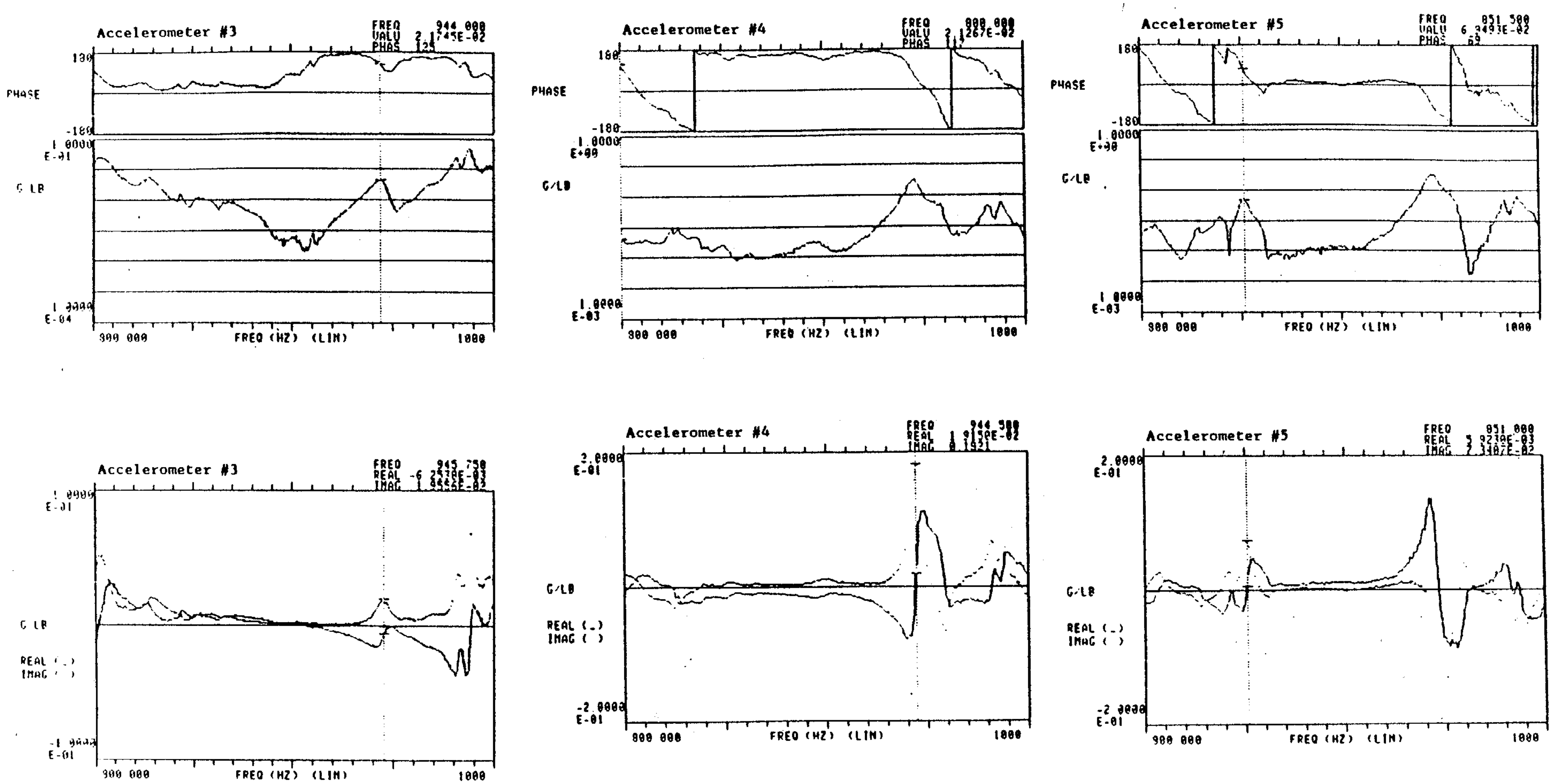
This is Figure 4. We were very surprised looking at the structure. We thought it would be a rather simple structure. We thought the mode shapes would be fairly easy to pick out. In fact, that was not the case. The modal density was quite high, and selection of the mode shape did become, unfortunately, a problem.

We are looking at three frequency response functions with the accelerometer on the main leg and the two accelerometers out at the other leg at a 45-degree angle.

The top plot is simply the loading plot. The bottom plot is of both the real and imaginery part of the frequency response. The way we select the mode shapes that will be extracted for the random decrement signature plots is simply by looking at this type of setup. We pick out modes that show up clearly, and to a high degree in the 45 degree leg, but show up to a lesser degree in the main body leg.

We are not interested in exactly what that mode shape looks like, but simply that it is a local mode and not a mode of the entire system.

In this case, you see the mode we picked up here is about 944 hertz. The accelerometer -- the response is to a much less degree that it is to the response on the 45 degree leg.



Accelerometer #3
FREQ 944.000
PHASE
G/LB
FREQ (HZ) (LIN)
Accelerometer #4
FREQ 944.500
Accelerometer #5
FREQ 851.000
REAL (_)
IMAG ( )

Figure 4

So that is what we used for our criterion for selecting the mode shape.

If we had more time, we would really like to do a minimodal survey and find exactly what that mode shape looks like. But for the random decrement signature, that is not really necessary.

This is Figure 5. To briefly go through the steps we used in extracting the random decrement signature, as I said, we first find the modes we are interested in, then shape out forcing function to excite those modes. We take accelerometers, and we get response measurements from the K joint.

We then set up a threshold crossing level and average the response time histories, taking positive and negative crosses -- a typical way of extracting the random decrement signature -- and normalize the signature with respect to the threshold level. The result is the random decrement signature.

We extract the baseline signature. That signature is really a signature of the structure in some initial state, which we hope to be an undamaged state.

We subsequently load the structure and extract signatures at intervals in the loading process. We correlate a baseline signature with respect to those signatures that we extract later in the loading cycle, and we monitor the correlation coefficient. The correlation coefficient then gives us an indication of structural integrity or structural degradation.

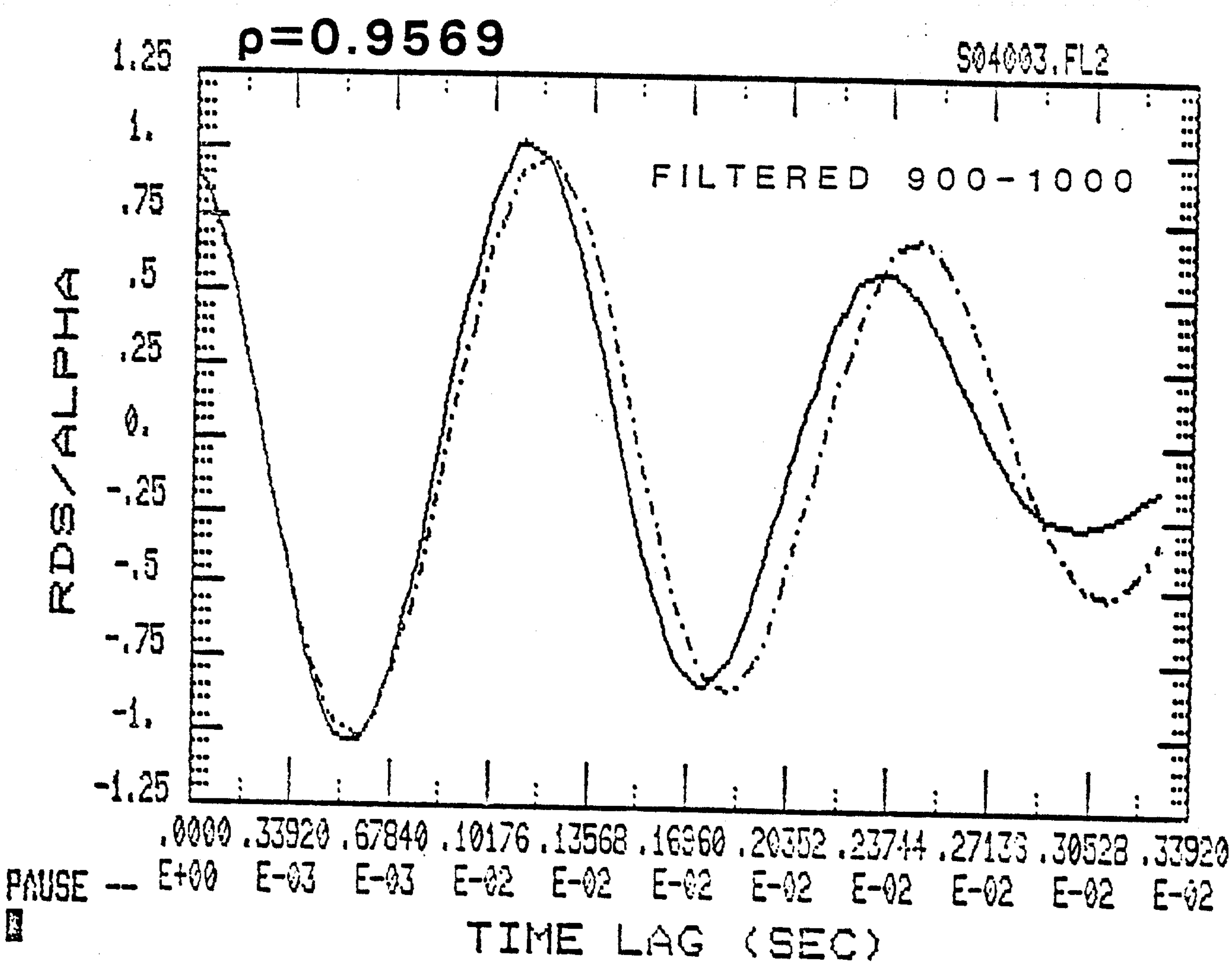
Figure 6 shows you some examples of the type of signatures we got and some problems that we had. First of all, let me tell you what each signature represents. The dotted line represents the baseline signature. The solid line represents the signature that we extract later on in the loading cycle. This one was extracted for Run No. 3 and from Accelerometer No. 4, which is about 5 centimeters down from the weld.

Run No. 3 corresponds to about 9000 cycles. So at this point we did not notice any damage in the structure. However, as you see in the correlation coefficient, there is some change in the signature.

RDS ANALYSIS METHOD

- EXCITATION WITH WHITE NOISE
- RESPONSE MEASUREMENTS (ACCELEROMETERS)
- SET A THRESHOLD CROSSING LEVEL AND AVERAGE THE RESPONSE TIME HISTORY ON ALTERNATING POSITIVE AND NEGATIVE SLOPES
- NORMALIZE WITH RESPECT TO THE THRESHOLD LEVEL
- RESULT: RANDOM DECREMENT SIGNATURE
- EXTRACT A BASELINE RDS, STRUCTURE IN A INITAL STATE, AND SUBSEQUENT SIGNATURES AFTER A LOADING CYCLE
- CORRELATE W/R TO THE BASELINE
- MONITOR THE CORRELATION COEFFIENT FOR AN INDICATION OF STRUCTURAL DEGRADATION

Figure 5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FILTERED 900-1000
RDS/ALPHA
1.25
1.
.75
.5
.25
0.
-.25
-.5
-.75
-1.
-1.25
.0000 E+00
.33920 E-03
.67840 E-03
.10176 E-02
.13568 E-02
.16960 E-02
.20352 E-02
.23744 E-02
.27136 E-02
.30528 E-02
.33920 E-02
PAUSE --
TIME LAG (SEC)

Figure 6

We haven't been able to calibrate the correlation coefficient. Roughly a change of 5 percent in the correlation coefficient corresponds to a change of about 2 percent in the signature.

There is about a 5 to 2 ratio for the number of points we have in the signature. As you increase the number of points in the signature, it becomes much more sensitive.

So we can actually -- which we haven't done -- calibrate the correlation coefficient for future use. At this point, there is some change in the signature, and the correlation coefficient does show that.

DR. YANG: Your second peak seems to be higher than the first peak, and your first peak seems to be higher than the initial state.

MR. ALEA: The solid line here you mean?

DR. YANG: Yes.

MR. ALEA: Is higher than what?

DR. YANG: Where you normalize it.

MR. ALEA: You are right. They both start out at the same level, but the one problem is simply that when you digitize the signal, you have a finite number of points in the signature.

The threshold level doesn't necessarily correspond exactly to one of those digital points. So when you normalize the signature, it should turn out to be one at each time.

MR. COLE: Actually, you would suspect there is an error in your analysis someplace. It might have gone from one down to say .8.

MR. ALEA: .8, right. I guess.

MR. COLE: It can't be equal at the peak there is something wrong.

MR. ALEA: The reason is the number of digital points in the signature itself.

MR. COLE: That is the measure of the error you have in your analysis?

MR. ALEA: That is correct.

VOICE: How many averages did you all typically take within your random dec signature?

MR. ALEA: About 500.

VOICE: You said this is filtered?

MR. ALEA: That is right. This is filtered from 900 to 1000 hertz.

MR. COLE: Are those overlapping?

MR. ALEA: Those are not overlapping. You start after the last one has stopped. So there is little correlation between the samples.

Figure 7 is a viewgraph for Run 17. Run 17 corresponds to roughly 75,000 cycles. The first indication of the crack was located at about 85,000 cycles.

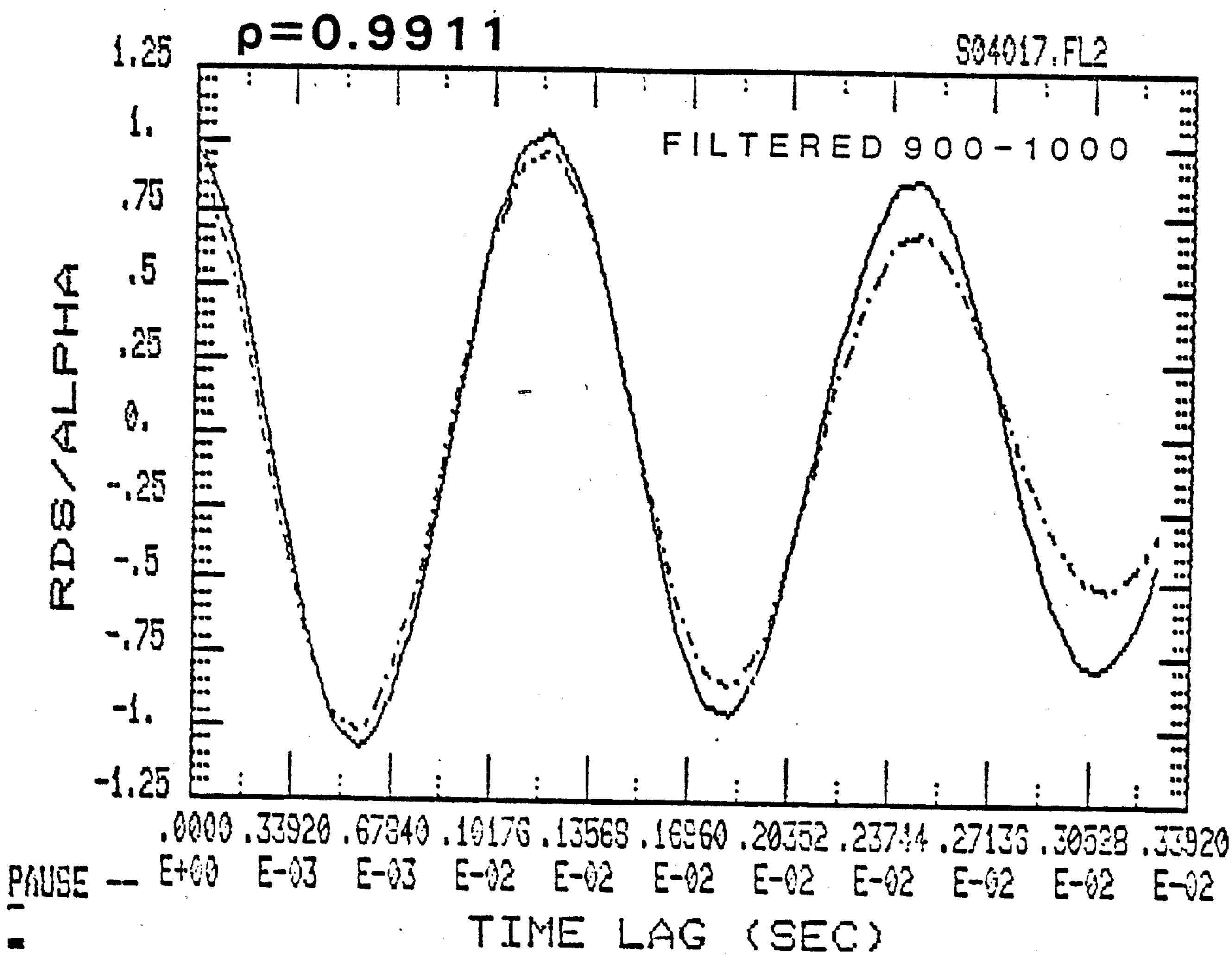
At this point you can see, still, little change in the correlation coefficient.

DR. YANG: Your negative part is also bigger than your positive part. I guess you attribute it to error in the data?

MR. ALEA: That is right, error in the digitizing.

DR. YANG: What is the sampling rate?

MR. ALEA: Roughly eight times the frequency of the mode. So it was 940 hertz, roughly 1000 hertz, to about 8000 samples per second.



ρ=0.9911
S04017.FL2
FILTERED 900-1000
1.25
1.
.75
.5
.25
0.
-.25
-.5
-.75
-1.
-1.25
RDS/ALPHA
.0000 E+00
.33920 E-03
.67840 E-03
.10176 E-02
.13568 E-02
.16960 E-02
.20352 E-02
.23744 E-02
.27136 E-02
.30528 E-02
.33920 E-02
PAUSE --
TIME LAG (SEC)

Figure 7

This is Figure 8. The first indication of failure we got in the random decrement signature was about Run 22. Before this the correlation coefficient did show some steady drops. However, before this point the drop wasn't significant.

Run 22, which corresponds to about 110,000 cycles, is the first indication of the failure. At this point the crack has grown to about 5-1/2 inches.

The final condition, where we check at the end of the test period -- Figure 9 -- is the one here. At this point the correlation coefficient has dropped to .2.

You also see a frequency shift in the signature. So we have shown here that, in the present state, we can detect a gross failure, but we still haven't calibrated the technique for detecting very small cracks. That is one problem we need to solve.

Figure 10 show that the second problem we have is filtering out unwanted modes. For instance, the fundamental banding mode of those two legs was about 144 hertz. However, there was another mode corresponding to a system mode, that we don't know exactly what it was, at about 179 hertz.

That system mode contaminated the first fundamental mode we were interested in. Unfortunately, we were not able to use that mode to extract random decrement signatures.

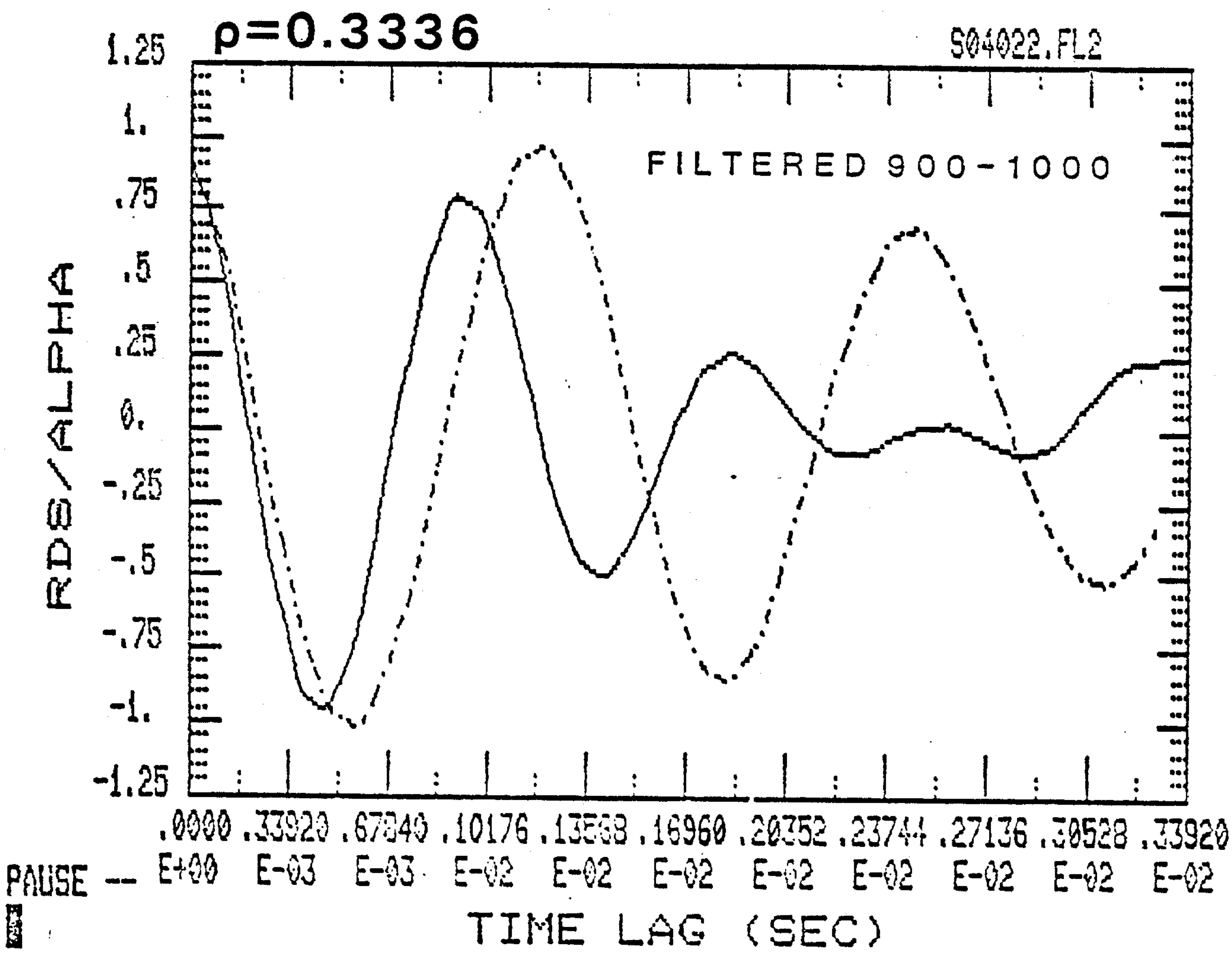
Maybe we can solve that by simply using a sharper filter, but that is a problem.

Also, exciting the modes to the desired level is a problem. Hopefully, we would like to start out by knowing what the mode is and shaping the forcing function to excite that mode.

But in some cases as in the case I just mentioned, if there is another mode, you also excite that one to a higher extent and it compounds your problem.

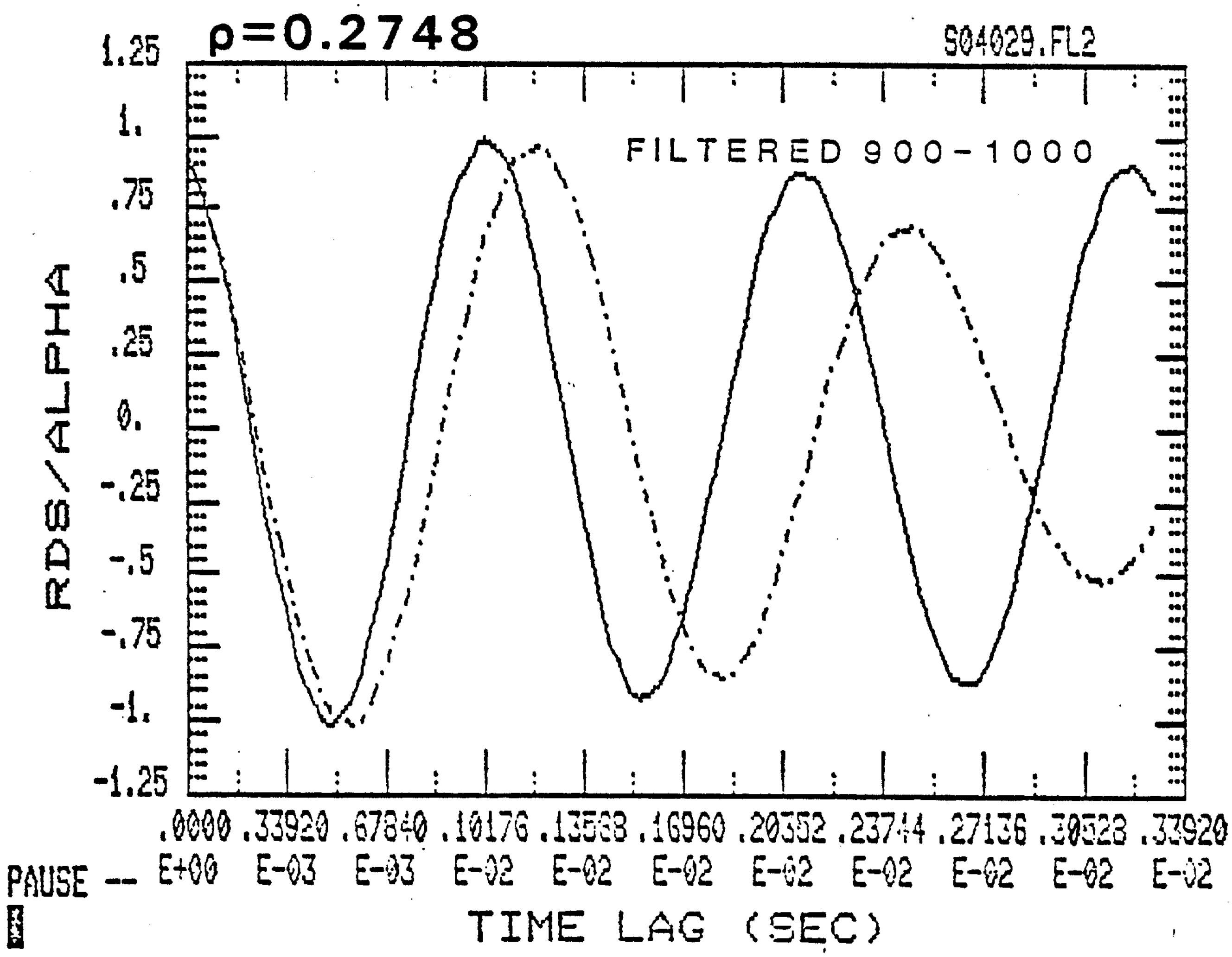
Figure 11 indicates that the next major application we have in store is on the cosmic background explorer at Goddard.

We would like to do the interface structure on COBE containing the instruments that will be flying on the spacecraft. What the project wants to do is cool the structure down to 2 degrees Kelvin. The structure is a riveted aluminum structure.What we would like to know is,



ρ=0.3336
S04022.FL2
FILTERED 900-1000
RDS/ALPHA
1.25
1.
.75
.5
.25
0.
-.25
-.5
-.75
-1.
-1.25
.0000 E+00
.33920 E-03
.67840 E-03
.10176 E-02
.13568 E-02
.16960 E-02
.20352 E-02
.23744 E-02
.27136 E-02
.30528 E-02
.33920 E-02
PAUSE --
TIME LAG (SEC)

Figure 8



ρ=0.2748
S04029.FL2
FILTERED 900-1000
RDS/ALPHA
1.25
1.
.75
.5
.25
0.
-.25
-.5
-.75
-1.
-1.25
.0000 E+00
.33920 E-03
.67840 E-03
.10176 E-02
.13568 E-02
.16960 E-02
.20352 E-02
.23744 E-02
.27136 E-02
.30528 E-02
.33920 E-02
PAUSE --
TIME LAG (SEC)

Figure 9

CONCLUSIONS

- PROPER EXCITATION OF DESIRED MODE SHAPES
- FILTERING OF UNWANTED MODES

Figure 10

FUTURE WORK AT GSFC

o COSMIC BACKGROUND EXPLORE (COBE)

1) ENVIRONMENTAL TEST OF THE INSTRUMENT INTERFACE STRUCTURE AT CYROGENIC TEMPERATURES (2 DEG KELVIN)

Figure 11

during the cooling process, do any of the rivets become loose. They are looking to us to help develop some way of defining if the rivets do loosen.

One of the possible applications is the random decrement signature. It is not the only application, but it is the application that we have the most experience in right now.

DR. PERRONE: Could you comment about -- you had another experience with random dec -- plate structures or whatever they were?

MR. ALEA: About a year ago we were asked to look at some large bulkheads from a pressure vessel. There was a composite structure that had delaminated during the previous pressure test.

We used the random decrement signature in that case to qualify the structure for another pressure test.

They wanted to know if, after the next pressure test, the delamination got any worse. We used the technique to show there was no more delamination in the structure. They went ahead and flew the structure, and as far as I know it is all right.

Mr. Henry Cole
Random Dec Computers, Inc.

MR. COLE: Before I talk about random dec, I want to comment on the Round Robin program. I work as a subcontractor with Jackson Yang. We kind of worked over the years on random dec. When Round Robin started, they were going to put weight all over the deck, and we were trying to figure out instrumentation.

We put our heads together, and put an accelerometer on the deck. Then we tried to figure out how we were going to analyze this. It turned out, they didn't put any weights on the deck. To make matters worse, in order to try to interpret some of the signatures, I built a little model with five bays, it's just a simple thing, and had the same number of levels, and cross-braces. It wasn't similar to the model -- just in principle -- but I got some very interesting things on that.

I would loosen legs and put different specifying instrumentation, and it turned out we didn't need it, and then they didn't even put weight on the decks.

The other thing is that random dec can be used with a lot fewer transducers, we found out, and I kind of see the random dec as being a resident package on an oil platform -- a small box that would be there and stay there through storms and everything and give a red light or something to someone wondering whether he's going to have to bail out or not.

That's the ultimate, I hope.

There are some things, I think, on the confidence level that I mentioned. We had 100 percent confidence in some of the diagnoses, but I think I should lower it to 99.6 percent.

We didn't try to locate any damage; however, there were some things that showed up on location which I thought were very interesting in my model.

(Slide) N/A

I just threw this model together. Actually, my model doesn't have these cross braces. This upper deck doesn't have a cross brace, so ignore that. But on damage scenario one, when we did that on random dec, we saw the signature, and it looked just like that. So I told Jackson that they loosened the leg on this thing. But we weren't absolutely sure, because my model was different than the original, but I found it very consistent, that if you loosen the leg, you find signatures like this. And if you look in the signatures in the Round Robin, you'll find this signature.

The point I want to make here is that I think that each type of damage on the platform will have a different signature. What we see here are fractures and members starting from level one, the base, five, four, and so on, up. Once you look at these things for awhile, you can see that they are all distinctive. I think it is possible to catalog damages, put them into a computer and when it sees a signature, look up the damage and say, "ah, the leg is loose there," or whatever.

Of course, the problem is, how are we going to get these signatures? I think that's where future research has to begin for random dec.

Those were just a few remarks I wanted to make, because my main talk isn't on this.

Regarding the origin of random dec, in general, I worked at Ames Research for many years on buffeting of space vehicles and airplanes, and we used to use spectral analysis methods. Then when we got into the Apollo program and the early parts of the Space Shuttle, we built an on-line autocorrelation computer. We were using it for measuring damping of systems that had nonlinear damping. They had nonwhite inputs, and it was a real tough problem.

We found that the trouble with the autocorrelation analysis was that it varied all over the map when we were in a test. So we started looking at ways to modify autocorrelation to kind of stabilize these signatures. So we did a lot of things.

Finally, we came down to random dec. It started with autocorrelation and went into random dec. Random dec was used for quite a while, and a couple of years ago, I guess some work done by Professor Vandever and his associates came up with a theory which said that random dec was just a crude approximation to the autocorrelation. In a paper he gave they also showed an example. And their random dec signatures were compared with autocorrelation signatures, and the random dec signatures didn't look very good. In looking at the way they obtained their random dec signatures, I found that they did not apply the latest techniques; they used some of the early, crude things we did.

So I have been in communication with him, and I would like to get their time history. Our problem now is interface. He has a PDP-11 format, and I have a different tape machine so you know those problems.

If we can get over that hurdle, I think it would be worth showing the differences.

I would like to say this about the work that they did. The paper they have is entitled "A Mathematical Basis for Random Decrement Vibration Signature Analysis."

The mathematics is very good, and they do provide a lot of equations which I think will be valuable for the foundation of the method.

Now we have to get the whole act together, get the analysis and everything, and experiment using standard methods. I find people applying random dec using many different methods.

The future of it is to standardize and use the same programs.

Now I'm going to show comparisons from a large data base we have, where we computed both random dec and autocorrelation and some mathematical relationships of the two.

Figure 1 shows that the random decrement method is simply an ensemble average of all the time histories which start at a given level, selected out of random data.

Right here you see some things different from autocorrelation. Autocorrelation is a mathematical process where you analyze the entire record. It's a purely mathematical operation. Random dec, you see, is a logic operation that starts with a selection.

The simplest form of random dec is where you select a level, then you accumulate all segments of the time history which occur at that level.

We talked with Pete Alea about some random dec calculations that do not perform this overlap of time histories. If you have lots of time, that's a fine way to do it, but it isn't as accurate. If you have a finite record, only so much data, the calculation is much more accurate by using the overlap.

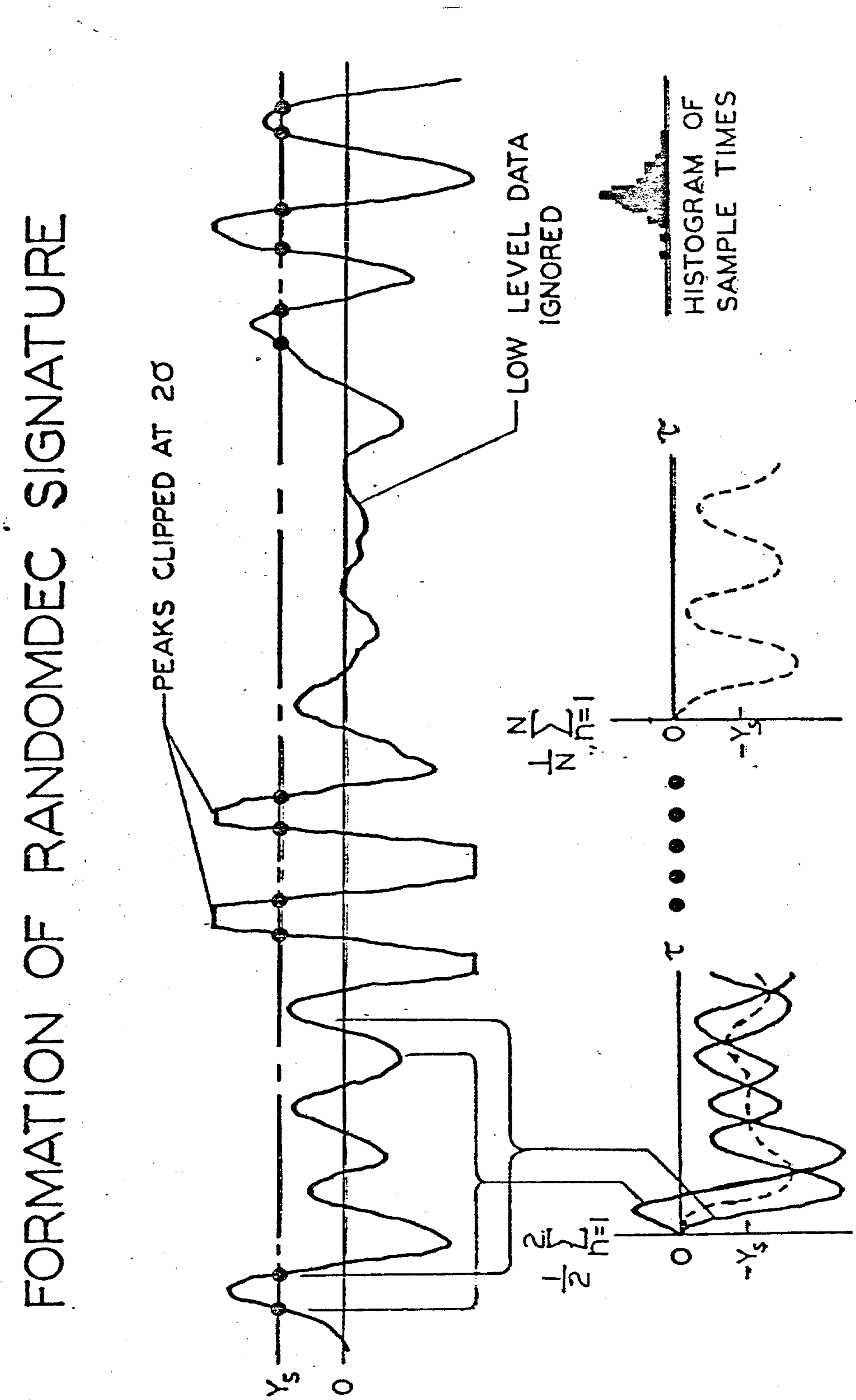

FORMATION OF RANDOMDEC SIGNATURE
PEAKS CLIPPED AT 2σ
LOW LEVEL DATA IGNORED
HISTOGRAM OF SAMPLE TIMES
Y_s
0
$\frac{1}{2}\sum_{n=1}^{2}$
$-Y_s$
τ
$\frac{1}{N}\sum_{n=1}^{N}$

FIG. 1

There are two things here that are different from autocorrelation. First, the random dec will overlook any low-level data. All this data down in this low level, which is usually garbage anyway, is included in an autocorrelation calculation, and it results in an error.

The other difference is that when you get saturation at the peaks in random data, random dec treats a saturated signal a different way than autocorrelation.

Actually, before I show you this part, I'm going to talk about forms of autocorrelation and random dec, how these signatures compare.

I am going to talk first about periodic signals, like a sine wave. If you put a sine wave through an autocorrelation, you get a cosine out. If you put a sine wave through random dec, you get a cosine out.

So for sine waves, they're identical.

This is Figure 2. However, for a square wave, the autocorrelation gives it a triangular wave. For random dec, you get a constant value, and if you want to get down into the mathematics, you find there are some impulse functions that occur at these points here. In experiments, these little impulse functions usually disappear. So, from this example here, you cannot say that in general, the autocorrelations and the random dec are the same for periodic functions.

DR. RUBIN: Vandiver's paper does not make that claim, does it?

MR. COLE: No. That's one thing I'm going to get into.

The paper was just for linear systems excited by white noise, Gaussin noise. But I'll get into that later.

I thought I would cover all signals, because in a total data acquisition system, you have to consider all the signals. A lot of times you have periodic signals mixed in with your random, so you have to know what's going on.

Now I am going to generalize.

This is Figure 3. Let's consider any signal that can be expanded in a Fourier series. That takes in a lot of periodic signals.

SIGNATURES OF A SQUARE WAVE

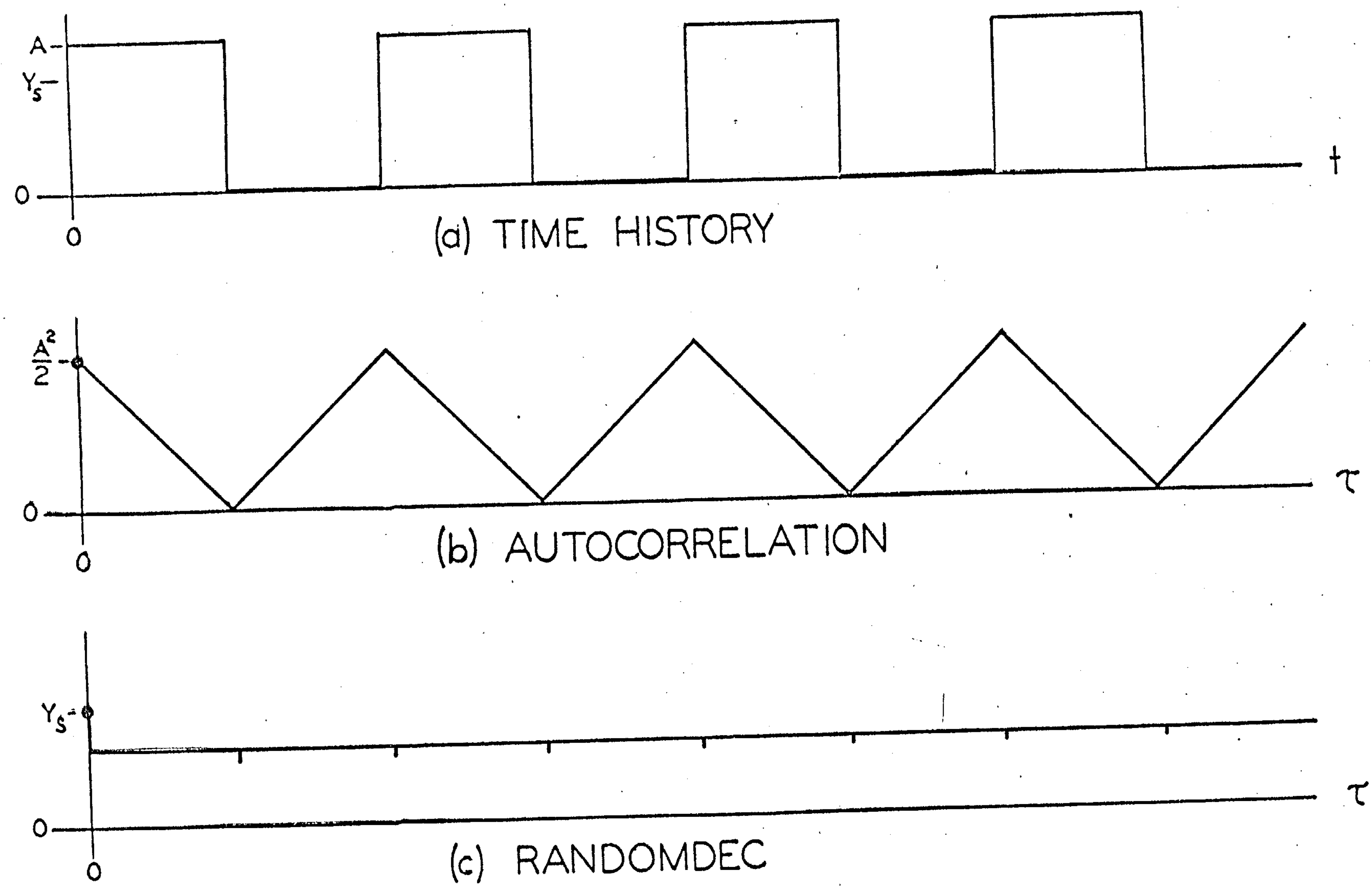


FIG. 2

FOURIER SERIES EXPANSION

$$\text{AUTOCORRELATION} \sim \sum_{n=1}^{\infty} C_n^2 \ \text{COS}\, n\omega T$$

$$\text{RANDOMDEC} \sim \sum_{n=1}^{\infty} C_n \ \text{COS}\, n\omega T$$

SIMILARITY REQUIRES:

$$C_n = C_n^2$$

Fig. 3

Take Y.W. Lee's Statistical Theory of Communication. There's an expression for the autocorrelation, in terms of the coefficients of the Fourier expansion. Consider the form here -- I've divided out the constant terms -- and you'll find the autocorrelation form is in proportion to the coefficient squared and wT.

Bob Reed and I, in a contract earlier, worked on the Fourier expansion for a time history. It's the same expansion, the Fourier series, and there are a couple references in which it is shown that the random dec is the summation of the coefficients, not squared. Look at these. There are the two forms. How can we possibly make these two curves similar. The only possible way I know is that the Cn has to be equal to the Cn\2~. That's fine for the sine wave because for a single term you can factor it out.

The only other solution we can think of for this is where Cn equals Cn\2~, where all terms for the Fourier expansion are equal. That sounds like white noise to me.

So you see, for the case of white noise, autocorrelation and random dec give the same form of signature. This, in fact, agrees with Dr. Vandiver's paper. It also agrees with our experience.

Now I'd like to talk a little bit about aperiodic signals.

Figure 4 shows that the procedure here is that you generate a computer-generated random time history. Take a random noise, feed it into your computer, calculate the time history, apply your method to the time history, and extract the signatures.

Since you know the parameters that you put into the computer, you can compare the results you expect with what you measure by the methods.

I'm showing here -- it says free vibration -- a case where you have white noise, a single degree of freedom system. You will find, for this case, that autocorrelation and random dec give the same signature in the limit. In finite time, there are some variations, but these are within what you might expect in an experimental system; however, there is a little thing that happens here.

This agrees with the theoretical paper.

I added 17 percent noise to this time history, and here's what happened. The random dec 17 percent noise we added to

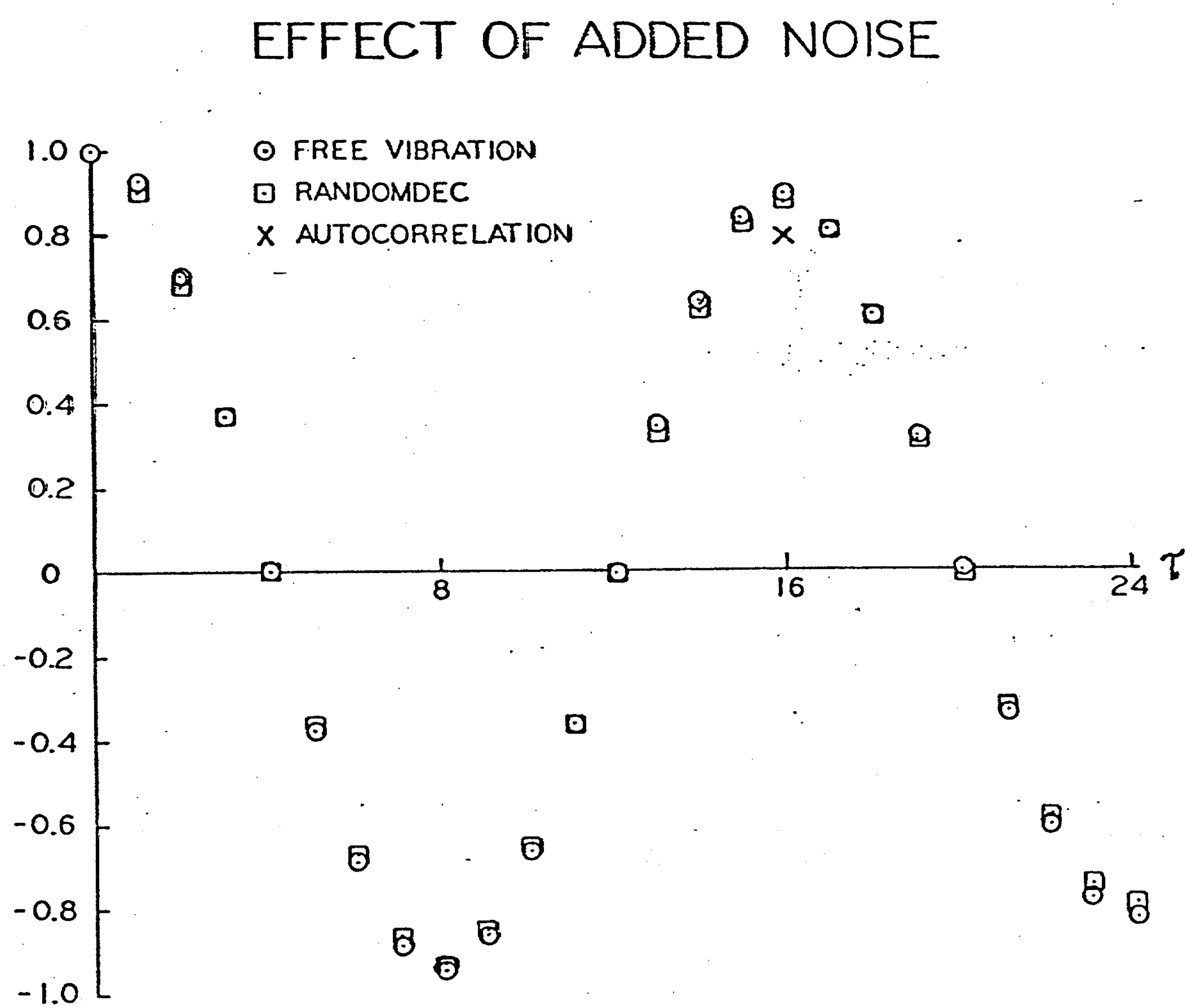

EFFECT OF ADDED NOISE
FREE VIBRATION
RANDOMDEC
X AUTOCORRELATION
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
8
16
24
τ

FIG.4

the time history created an error in the random dec down to here. For the autocorrelation on the same time history, it created an error down to here.

If you're measuring damping out of this system, this 17 percent noise created a 20 percent error in the damping measured by random dec, it created an 85 percent error in the damping measured by autocorrelation.

Now, the theory really doesn't get into this properly, but that's what I want to point out here. There are a lot of practical things which show up in experiments and measurements that are important.

This is Figure 5. The next thing I'd like to show, is the effect of nonwhite noise.

The theory assumes white noise, but in most cases, you end up with nonwhite noise, and we were concerned about this. We had isotropic turbulence on our model, which is found quite a bit in aerodynamics. It's a spectra which comes out, and then it falls off on a log plot.

We were interested in what effect this would have on our signatures. We have been running autocorrelation. We developed this curve for autocorrelation, and the distortion is the measure of the height of the signature here, relative to an exponential term which gets added to this by the nonwhite input.

When we ran this for random dec, we found out that the distortion on random dec was one-half the distortion on autocorrelation. So here again, we see that a practical thing, nonwhite input, has less effect on a random dec signature than on an autocorrelation.

Now I am going to get into another case which should be covered by the theory. This is a two-mode system. You have two degrees of freedom. It is computer-generated. It has white noise input.

The case here is for two modes that are fairly close together, and they have different damping ratios.

Figure 6 shows that this is for small-time lags, and we say, "Aha, they are the same here," and the theory says that they should be the same when your systems are the same; however, if you look at larger time lags -- Figure 8 you find a fairly large difference which occurs between the

(Note: Text does not reference a Figure 7.)

DISTORTION EFFECT OF ISOTROPIC TURBULENCE INPUT

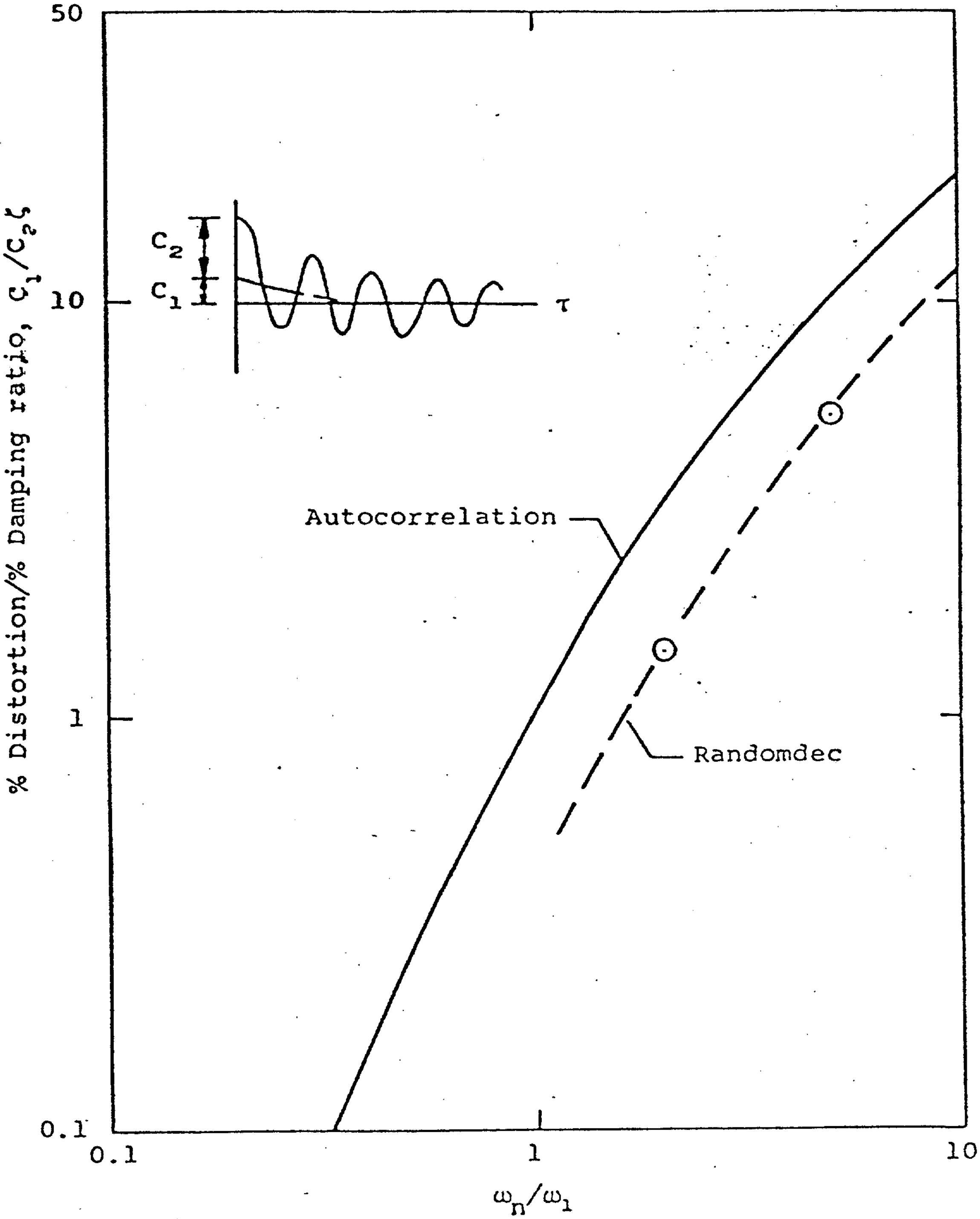


FIG. 5

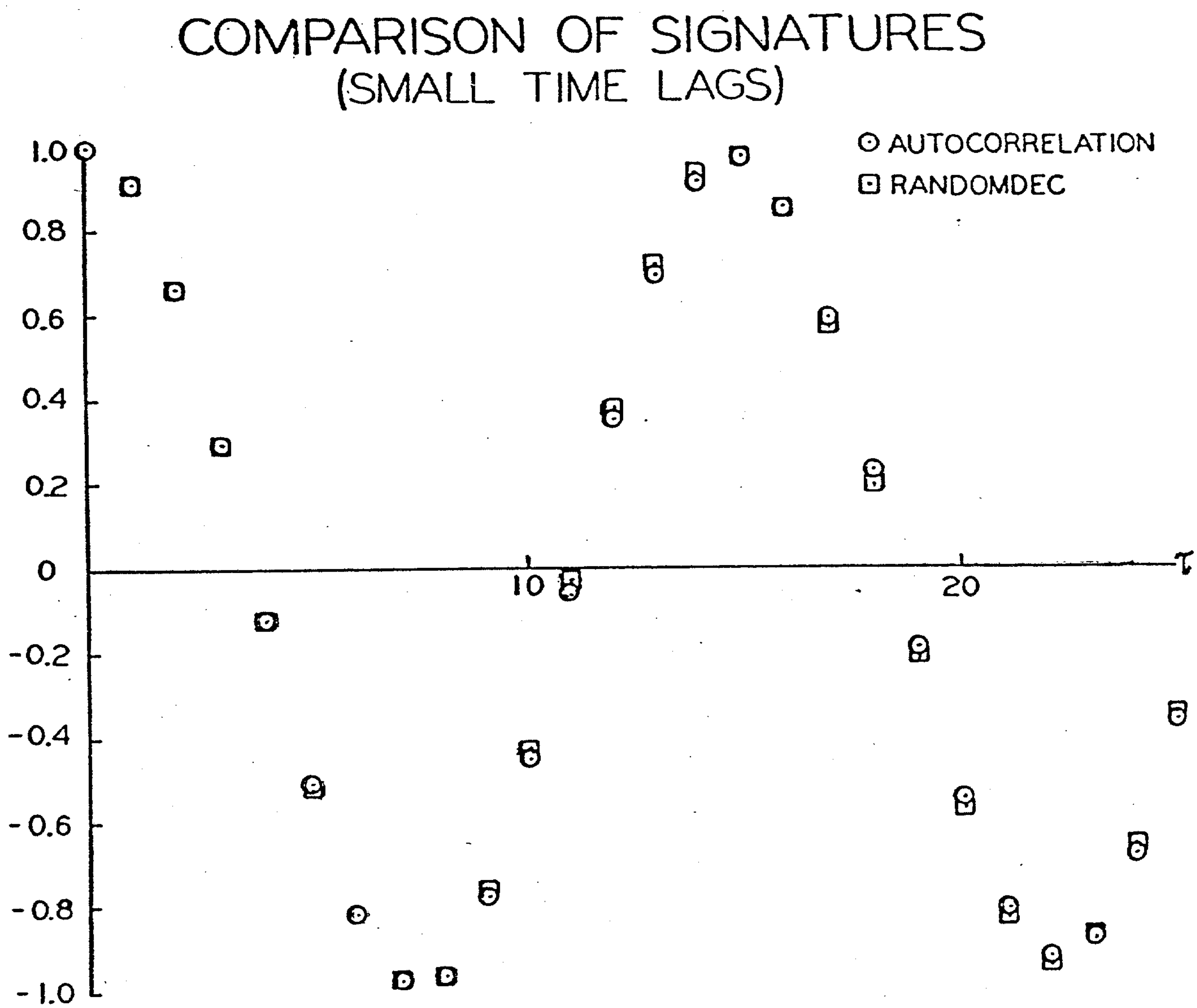

COMPARISON OF SIGNATURES
(SMALL TIME LAGS)
AUTOCORRELATION
RANDOMDEC
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
10
20
τ

FIGURE 6

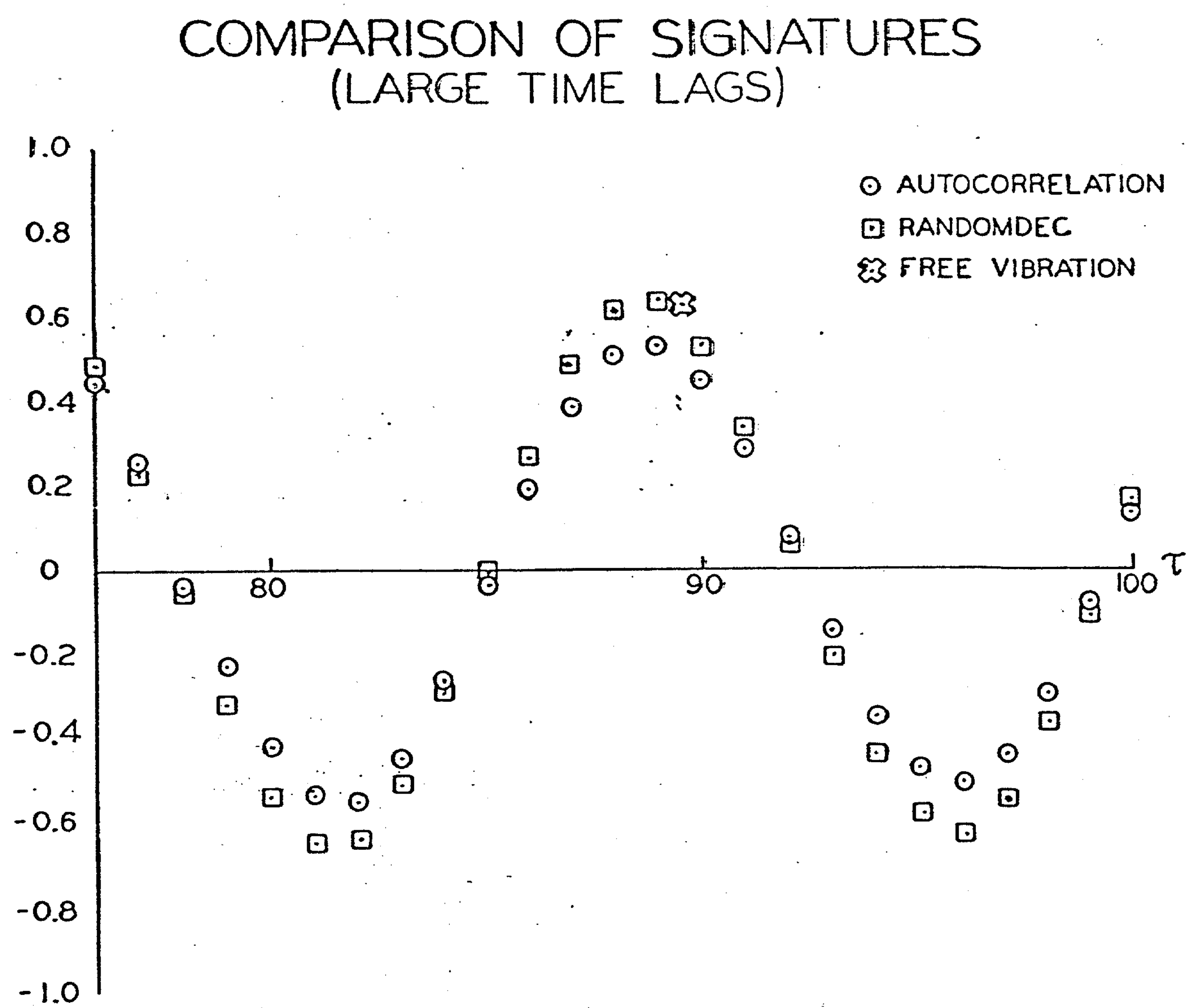

COMPARISON OF SIGNATURES
(LARGE TIME LAGS)
AUTOCORRELATION
RANDOMDEC
FREE VIBRATION
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
80
90
100
τ

FIGURE 8

autocorrelation and random dec. This difference cannot be explained by any statistical variance or anything.

One of the things a lot of people leave out of the random dec is the accuracy statement. That's one of the problems in this paper I have been reviewing, that they didn't give any accuracy statements for random dec. Anytime you take random dec, you have available to you an accuracy statement. You know at this point it will be here with a confidence level of so much variation. So this is outside that.

For this case, take these two modes, displace them equally, let them go. It falls on the random dec curve. I now suspect that the autocorrelation may be the free vibration curve with a different set of initial conditions. Perhaps there is another free vibration curve which will fall on the autocorrelation. That remains to be seen, but the point is that here is a case where the theory does not agree with an experiment.

That is one of the things about the mathematical foundation. We need more work explain some of these things.

DR. SUNDER: How much of this would you relate to your way of computing the correlation versus somebody else's way of computing the correlation?

MR. COLE: These were done digitally, and these are generated by computer, and they have been checked many times. The first time I presented this particular one, it was run, and I only had one point on the autocorrelation because we ran out of money in the program to calculate all the points. Since then, we have reviewed it, recalculated it, put in the extra points on autocorrelation, and they do agree.

Now I agree, there is always a possibility of an error.

DR. SUNDER: I'm not concerned with the error as I am as the number of samples you used, the data links you used -- you can play around with those numbers.

MR. COLE: No, that's why whenever I do anything like this, I have an accuracy statement on the points. I know whether they've converged -- what the variations should be -- and autocorrelation isn't quite as neat because all points are varied -- the starting point -- you have variance on all the points.

Random dec locks in the first point and you have different statements of accuracy for each point as you go out in time. That gets into some pretty complicated things. People speculate on what these accuracy statements should be, but a lot of this has already been done, and it's in the literature. People just don't look far enough back to get it.

VOICE: Do you use a biased or an unbiased autocorrelation estimate? You have a reduced variance number, and the net effect is that the biasing drops the values. It's like a window on the estimated autocorrelation.

MR. COLE: I know what you mean. In this thing we made sure that for the time lag we had, the biasing was not significant.

I'd like to get on to another case. This is the real problem we're in.

Figure 9 is actually from some experimental data. It was a case where we had non-linear damping. You might think of this curve as being the free vibration decay curve of the system after displacement, and we have a log scale here. So if damping is linear, you get straight lines.

Now, when you apply white noise to this, you get signatures, and you find that a band-width of spectral density will give you this kind of an answer. From autocorrelation, if you take an initial start, you get this answer, and with random dec you'll get a lot of different answers, depending on what level you set your trigger value at.

This is an area which was treated somewhat by Dr. Caldwell in a doctoral thesis at Maryland. We did some experiments in this, but I think part of the future work should be the ability to treat non-linear damping systems. I suspect that a lot of these fluid systems -- and I'm pretty sure that the oil platform will get into the same thing -- where you have a vibrating system, a fluid, and separated flow and turbines, you're going to have non-linear damping.

I just wanted to show this so that we remember that in real situations we do have a problem of connecting all these methods. This also demonstrates what was happening to us in our wind tunnel where we had different levels of random input.

In a random input, if the intensity of the input goes up, then this curve goes up here. That means the spectral

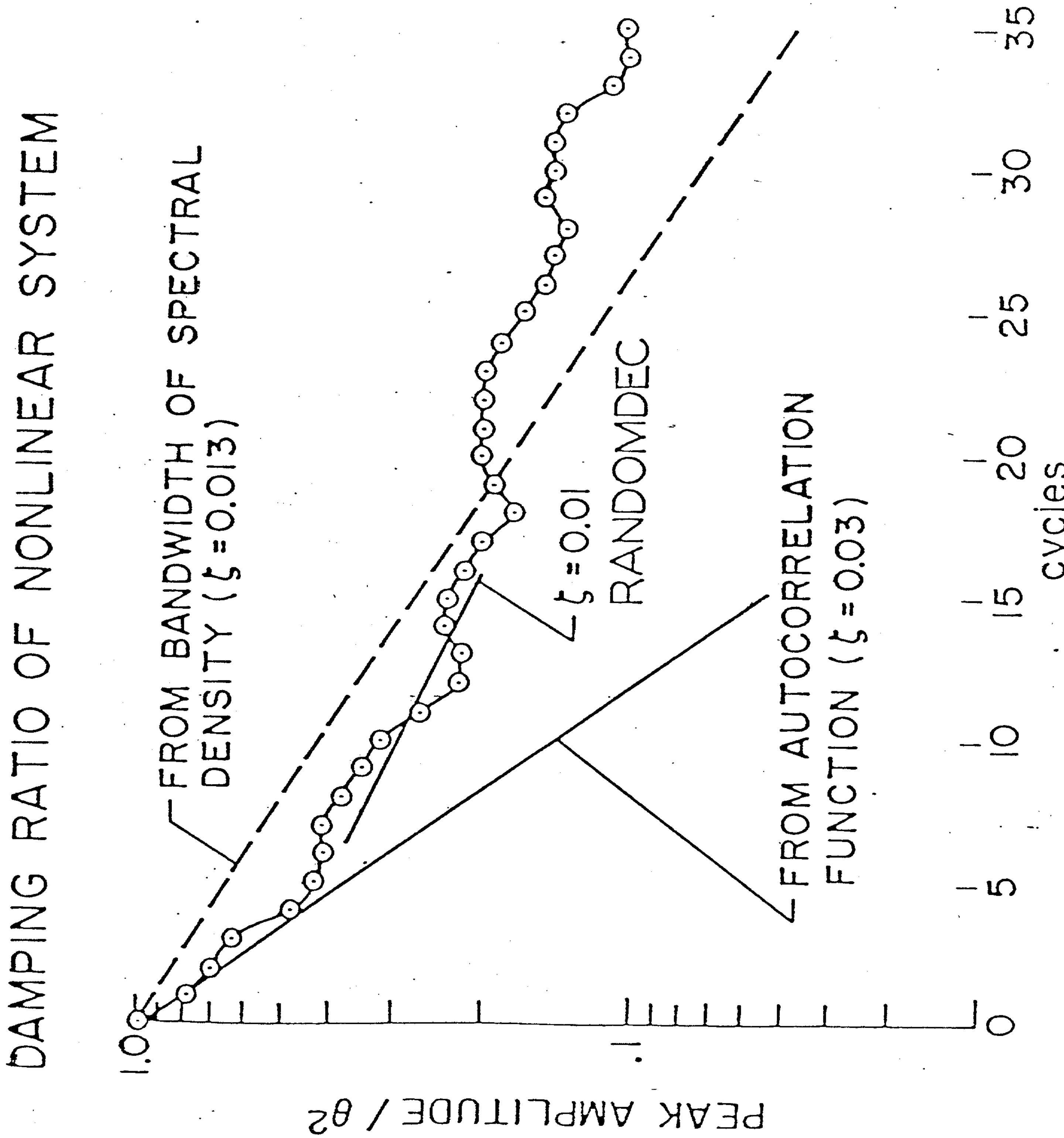

DAMPING RATIO OF NONLINEAR SYSTEM
FROM BANDWIDTH OF SPECTRAL DENSITY (ζ = 0.013)
ζ = 0.01
RANDOMDEC
FROM AUTOCORRELATION FUNCTION (ζ = 0.03)
1.0
.1
PEAK AMPLITUDE / $\bar{\theta}^2$
0
5
10
15
20
25
30
35
cycles

FIG. 9

density is now averaged from a different point. The autocorrelation is averaged from a different point. The random dec, though, is locked into a given level, and it is much less sensitive to changes in random input. This is why it's good in experiments.

Figure 10 is a review slide of what we're talking about. These are the signal types, description, and over here we say, "do they have the same form or not?" Periodic signal, Sine wave? Yes, they are the same. Square wave, no.

Fourier series, All coefficients equal? Yes, you get the same results. Unequal? No. White noise. Yes? Single degree of freedom white noise? Yes, with a little qualification on finite time. Aperiodic, but with noise added? No.Non-white noise input, Unequal damping? No. Single degree of freedom, non-linear damping, Non-white noise? No.

So there are specific cases here where we do agree, and there are a number of those where they do not agree. I'd like to add one more case to this, and I really hate to do this because Professor Vandever isn't here, but the example given in their paper is another case which convinces me that they are different, because the damping value that they get for autocorrelation is .010.

Now, for the MEM method, the spectral method, they get .014. Then they have a variation on it. By the random dec they got .016. Now in the example they show, the damping value from random dec falls within the accuracy statement of the MEM. The autocorrelation falls far outside of that.

Right now we don't know whether that's due to the way it was calculated. So I think that's something we'll try to clear up in the future.

DR. YANG: Actually, what you're referring to is based on Dr. Campbell's thesis with the work of Professor Vandever. He is highly qualified on that particular subject.

DR. CAMPBELL: Let me make a comment. I guess one of the things that has come from the work on damping is that when you finally extract damping from the random response of the system, no matter what technique you're going to have, or what technique you use, there is going to be associated with it certain confidence bounds on the data. In trying to extract damping with the autocorrelation, if you had gone in and changed some of the parameters and weighed just a few of

COMPARISON OF FORMS OF AUTOCORRELATION AND RANDOMDEC

Signal Type	Description	Same Form?
Periodic	sine wave	Yes
Periodic	square wave	No
Periodic	Fourier series (all coeff. equal)	Yes
Periodic	Fourier series (coeff. unequal)	No
Aperiodic	white noise	Yes
Aperiodic	Single-degr. of frdm. Input=white noise	Yes*
Aperiodic	Same as above but with noise added	No
Aperiodic	Single-degr. of frdm. Input=nonwhite noise	No
Aperiodic	Two-degr. of frdm. (unequal damping) Input=white noise	No
Aperiodic	Single-degr. of frdm. (nonlinear damping) Input=nonwhite noise	No

* differences occur in finite time

FIGURE 10

them, you would find that you would get a little bit different damping estimate.

In fact, if you use the Fourier transform method, you would find out that you would get damping estimates that go down to a very small fraction of a percent, all the way up to 10 percent, strictly based on how you computed that number.

There is associated with it a bias, and as you change the process and those two statistics change, you have no way of knowing where they are. So our baseline recommendation is until you can get statistics on computing damping estimates from Fourier transforms and autocorrelation functions, you have no idea whether you are getting a highly biased answer or not. The MEM method is one method that provides you with that statistic and lets you know wherein is the right answer.

MR. COLE: That's great, because I think this is part of our problem. I don't like to admit it, but there is a very, very small bias error in random dec, too. But it is very small, and here again, all these things are a lot alike. It all depends on how you calculate it. I'm amazed at all the different ways that people calculate random dec.

There are two ways that it's done. Some people take a time history on random dec, they digitize it. Then they worry about biasing errors and all these other things -- how they filter the data.

But if you run random dec with the analog signal the way I do it, you don't have any digitizing errors.

Another thing which makes a difference, like on the Round-Robin, the tapes I analyzed were copies of the original tape. Then I got a copy of the copy. Some of these had a lot of spikes on them, so I had to put a logic circuit in the computer which, if it sees a spike, throws out that particular segment.

The thing about it, is that you have to keep track of your bias errors, and also the variances of your measures.

DR. CAMPBELL: In those variances there is a lower bound, no matter what technique you use, It doesn't matter. There is a minimum confidence bound based strictly on the characteristics of your system and the random input. And there's no way around it.

MR. COLE: Well, now there are certain ways around it.

DR. CAMPBELL: The point I'm addressing is strictly random excitation. As soon as you have that, there is what is called a Kramer-Rao bound. That is fundamental limitation on your ability to estimate a quantity from N samples of that data.

MR. COLE: You're right.

If you have a narrow-band system and you expand it out, in Shannon's sampling theory, you can only get two independent values per cycle of that data.

If you take all the points and average them, you aren't going to do much better. However, it turns out in overlapping, for example, the example you ran in your paper -- you had somewhere around 80 samples where you took long segments that were separated out. If you used overlapping on that situation -- and I recognize that you weren't set up to do that, but you would have ended up with over 800 samples, and according to the accuracy statement, that degraded the results about 50 percent.

But I checked on the variance of your result, and it checked with the theory. So I'm sure your results are right, and I think that we can get together and compute these things in a better way, and then find out what's really happening.

DR. SUNDER: I would like to show two new graphs, if I may. We have also looked at the random dec approach, particularly after Kim Vandever's paper, and I think the spirit of the paper needs to be kept in mind. It is trying to see if the random dec signature is indeed invariant with the type of excitation. Which means, if you have a non-linear excitation, does the signature get affected? That was the motivating factor behind the derivation, and not particularly the fact that it's white noise.

(Slide) N/A

To test that out, we essentially used the Pearson-Moskowitz spectrum to sort of simulate a non-white situation. This is the situation where you use the single cylinder with a unit diameter and a unit height at the water level. The crossing period is 2.8 seconds and the damping level is .05 percent. This had a natural frequency somewhat like that.

But if you look at this, the random dec signature is computed and you find it looks pretty good. You do the same for a different sea state. Essentially what I'm going to do now is change the crossing of the spectrum from 2.8 seconds to, let's say, 10 seconds -- a hypothetical case.

DR. YANG: Is your first pole zero?

DR. SUNDER: Yes

MR. COLE: A different calculation.

DR. SUNDER: We've done it also with other decrements. I think the final results that come out are still the same.

(Slide) N/A

Now look at the situation. You have not a unimodal response spectrum anymore; you have bimodal, because the first peak is also dominating, and you find a significant difference now in the random dec signature.

If I superimpose the two -- I think it's the same time scale -- there is a significant difference. Now, if I were in the situation of having this kind of result, what we did was to also look at evaluation of damping. In particular we tried to estimate damping from these to examples, and we used the ITD method.

The ITD method provides an outlet for noise, which means I get more with the spectrum in a 2-degree of freedom system rather than a 1-degree system. We found the damping measurements using ITD with random dec input significantly better and closer to the true value than using a damping measurement derived simply from the random dec signature.

So in a sense, to base your judgement on the damage purely from the signature might not be the best way of doing it. I' might be better to also look at the other parameters.

MR. COLE: I agree with you 100 percent. This is the thing you have to recognize when applying the method to damage. You have to be very careful to make sure you have an idea of what the spectrum of your input is.

You don't have to know it exactly. You know that the random dec is less sensitive than some other methods, but it will affect the signature, there's no question about it, and that's what that one figure I showed was -- the isotropic turbulence.

Of course, when you get to a peak spectrum like you have there, I'm not surprised you have those big differences. And these are things you just have to remember.

MR. WARREN: Harry Warren, from Mega Engineering. I'd like to ask you a question off the major point of your talk. You mentioned the idea of using a catalogue of random dec signatures as a way to look at complex structures to determine where damage occurs, by having a computer match-up against this sort of library.

I'd like to ask how might that be as an area for future research relative to what Dr. Yang has mentioned as an area for future research; that is, deriving modal parameters from random dec and from that point, moving to a locational idea.

They seem to be very different to me. Are they somewhat related?

MR. COLE: I'm sure they're related, and I think we have to explore different methods and decide what's feasible. There's only so much money. You can always think of more methods than there is money to do them. But I think it's something we'd have to just put our heads together and think about.

Charles McCogney
Federal Highway Administration

NDE Testing Program State-of-the-Art at the Federal Highway Administration

The Federal Highway Administration has been pursuing research in nondestructive inspection for approximately the last 10 years. It all happened after the collapse of the Point Pleasant Bridge in late 1967, where considerable attention was focused at that time on bridge inspection.

Whereas bridge maintenance and inspection is the primary responsibility of the bridge owners; that is, the State Highway Departments and Municipalities, the Federal Highway Administration, through an act of Congress, was ordered to assume certain responsibilities relating to safeguarding highway structures.

In compliance with the 1968 Highway Act, National Bridge Inspection Standards were developed. These Standards apply to all structures defined as bridges located on any of the Federal-aid highway systems.

A bridge is defined as an opening having a 20 foot span or support from abutment to abutment. All highway departments were to set up inspection organizations with qualified personnel who, if not already experienced in bridge inspection, must take the comprehensive training course.

Each bridge is to be inspected at regular intervals not to exceed two years, but depending on each individual case, they could be inspected more often. The details of the inspection are made according to the Manual for Maintenance and Inspection of Bridges. This is prepared by the Operating Committee on Bridges and Structures of the American Association of State Highway and Transportation Officials, better known as AASHTO.

The role of research in the inspection of bridges in the Federal Highway Administration is to provide the State Bridge Inspector with a better tool to inspect.

For routine bridge inspection by the State Bridge Inspector, we would like the instrumentation to be lightweight, portable, simple to operate.

However, in recent developments, where we have endeavored to relieve the inspector of having to make questionable decisions as to the integrity of bridge components, we have developed more sophisticated instrumentation that includes automatic recording and processing of data, and in some cases, the added capability for realtime or near realtime display.

With that introduction, I would like to show a number of slides here depicting some of the research and development for nondestructive evaluation that the Federal Highway Administration's Office of Research and Development has accomplished.

(Slide) N/A

This is a familiar picture. The Point Pleasant Bridge collapse. There were something like 37 or 40 deaths. But this was all triggered by a very local mechanism.

(Slide) N/A

Not this I-bar, but one like it.

(Slide) N/A

You see the stretched erosion pit; you see the arrow pointing to it. This is a design where if one bar failed, the whole bridge came down -- and did.

I don't know at that time whether the bridge inspection capability we had would have been able to detect it or not. Today, maybe so. And hopefully in the future, we will be able to detect such a small crack.

(Slide) N/A

Some of the cracks are very small, very, very difficult to see. This is Dr. Fischer of Lehigh University looking through a 10-power magnifier there trying to detect cracks in these cover plates on a bridge in Connecticut. I had a hard time finding them; he seems to be able to pick them up. That is the type of thing we are sometimes confronted with.

(Slide) N/A

In another case, there is an 11-foot crack. It should have been found long ago. The only warning they had is the fact that they were having six inches of deflection a day.

(Slide) N/A

These are some of the methods we have explored. Some we actually sponsored. Acoustic emission, acoustic

ACOUSTIC CRACK DETECTOR (ACD)
SURVEY UNIT
FOR LOCATING CRACKS

Features

One hand operation.
Audible and visual crack indication.
Digital readout on probe automatically indicates distance from probe to crack.
Coupling indicator.
Battery condition indicator on probe.
Easily calibrated for various surface conditions.
Can be worn as backpack or frontpack.
Accessory belt for couplant, cleaning tools, positioning fixture, measuring tape, etc.
No electrical shock hazard.

Capabilities

Range—3 to 10 ft probe to crack, typical on bridges, depending on surface conditions and preparation.
Sensitivity—detect ⩾ 3/4-in. crack with high reliability over operating range, shorter cracks at close range under some conditions.
Discrimination—will not alarm on good welds without heavy undercut.

Specifications

Battery powered—~8-hr operation, rechargeable using separate charger (furnished).
Size: 10-1/4 in. X 12-1/4 in. X 2-1/4 in.
Weight: pack 8 lb; probe 1.2 lb.

FIGURE 1

MAGNETIC CRACK DEFINER (MCD)
UNIT FOR DEFINING PRECISE
LOCATION AND LENGTH OF CRACK

Features

One hand operation.
Audible and visual crack indication.
Lamp illuminates on probe indicating presence of and direction of crack.
One channel detects open cracks and cracks along the toe of welds.
One channel detects crack tip(s) in parent material.
Both channels operate simultaneously.
Complements ACD.
Probe can be used to determine precise location and length of crack.
Paint removal not required.
Battery condition indicator on probe.
No electrical shock hazard.

Capabilities

Crack definition—indicates crack length within 1/4 in.

Specifications

Battery powered—~1.2 hr operation, rechargeable using separate charger (furnished).
Size: 10-1/4 in. X 12-1/4 in. X 3-1/4 in.
Weight: pack 14.6 lb; probe 0.5 lb.

FIGURE 2

birefringence, magnetic field disturbance. We have done quite a bit in ultrasonics, x-ray diffraction. I should add random dec. We did a little work on that, too, some years ago.

Figure 1 shows our early endeavor with the acoustic crack detector. This was Southwest Research Development. These are the features of the system. It has audio output, a digital readout instead of an oscilloscope. You have got just a digital readout of the nearest reflector. These are the features of the magnetic kind of an eddy current device. I' gives you an indication of surface cracks and which way the crack is oriented.

Figure 2 shows that the unit is about as simple as I think you can make something. You just put it on there and probe around and listen for the alarm.

We now have upgraded it a little bit where we have a proximity tone that goes on when you come near the crack. As you hit the crack, it changes tone.

(Slide) N/A

This is the reason why these things have got to be compact and portable and self-contained types of things.

This is the basket these guys are on going up for the bridge inspection.

(Slide) N/A

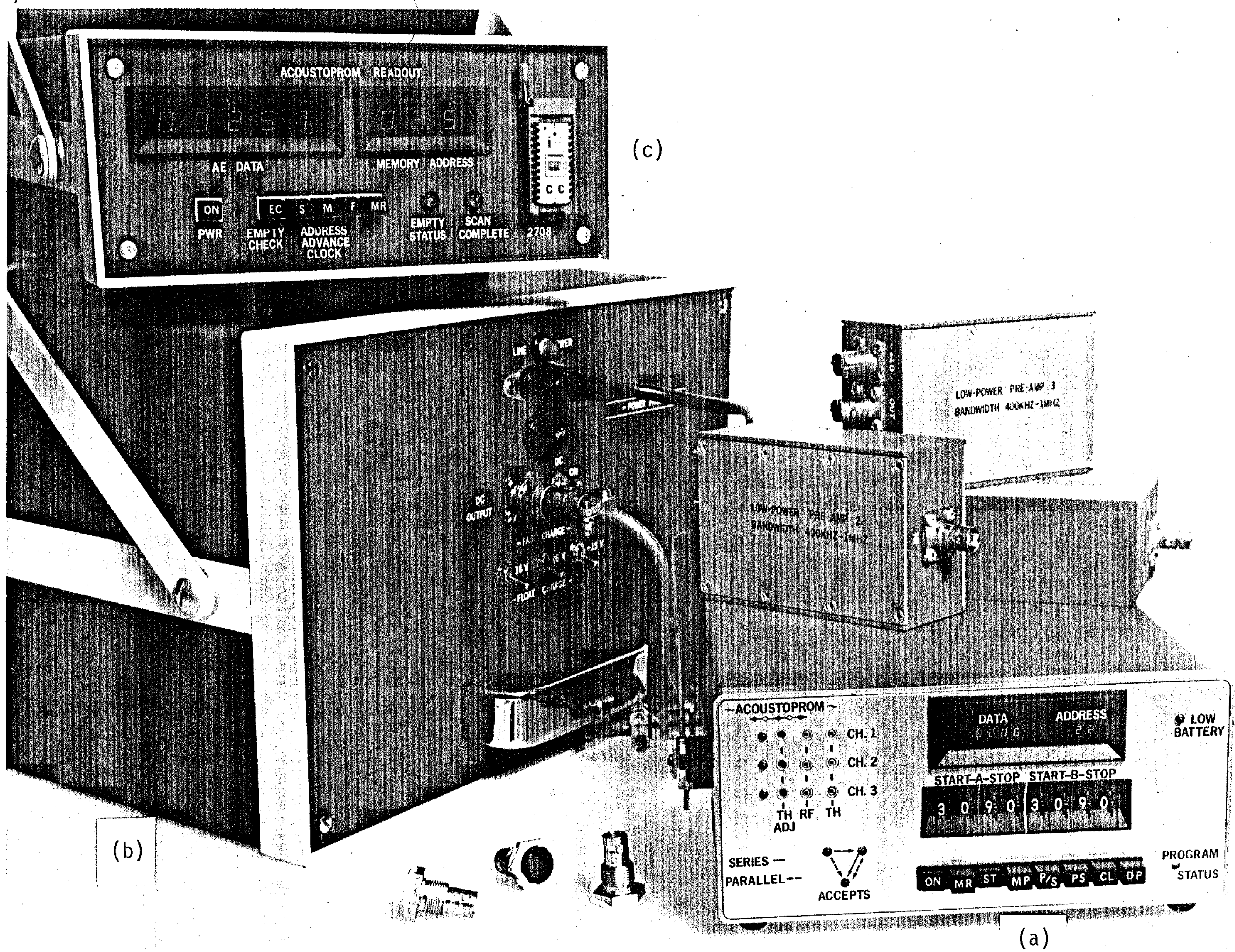
It is even more scary when you get up there. This guy -- I don't know whether he is tied off or not. I don't know whether he is defying the safety standards of the state or not, but he is one of the riggers that were up there.

(Slide) N/A

You can see the probing you have got to do to get up there and inspect. The only access you have in this case is around the periphery of the bars. You have got to go around and look for cracks. You have to shoot your wave in tangentially to pick up any radial cracks. But you see the compactness of the unit. It has got to be that way.

(Slide) N/A

This is an I bar probe on another bridge. It shows them probing around back up into the bar. You see the digital



FHWA Digital Memory AE System

FIGURE 3

readout here, 2.3 feet to wherever he is getting the deflection in that bar.

(Slide) N/A

Here, he is looking at a radial crack. There is a lot of serious corrosion on the pins. Here the indication is that there is a crack radiating up this way. If there were a crack running that way, then this light would go on.

(Slide) N/A

Figure 3 shows the digital memory acoustic emission system. This was developed at Battelle Northwest. This is a three-channel system for monitoring a known area. They have the readout unit here with the address, the number of counts, the three amplifiers, the sensors, the power supplies, which have been considerably reduced in size.

The system generates data on EPROM chips which you put in here, and you can read out the address and the number of counts that came from that particular location. It is kind of a histogram you get out of this. It has a 24-hour clock in there, so you can take data in any kind of interval you may want: a second, or two seconds, or an hour, or half-hour, or whatever. The system then tries to identify a source location.

(Slide) N/A

These are the chips, incidentally. These are erasable, nonvolatile used in the system.

This is Figure 4. Here is the thing about this that made it practical, in a way. This is called parallel mode of source isolation. You set up three transducers. You can pretty well narrow down the acceptance area for acoustic emission. This on the other hand, is the series mode where the area of interest would lie outside the triangulation of the three transducers. By using different pairs of sensors, we are able to get the plan location even though it falls outside the triangulation.

Figure 5 shows a typical histogram with the valid data coming in being accepted from that area as opposed to the background noise, which is also monitored at the same time. The count is in the neighborhood of less than 10 here. We monitored this particular bridge June 25 through July 5. That is typical of what you would get. Now, we don't know yet about how big the influence of the traffic is on it. It

AE MONITOR - BRIDGE FLOOR BEAM FLAWED AND UNFLAWED AREAS

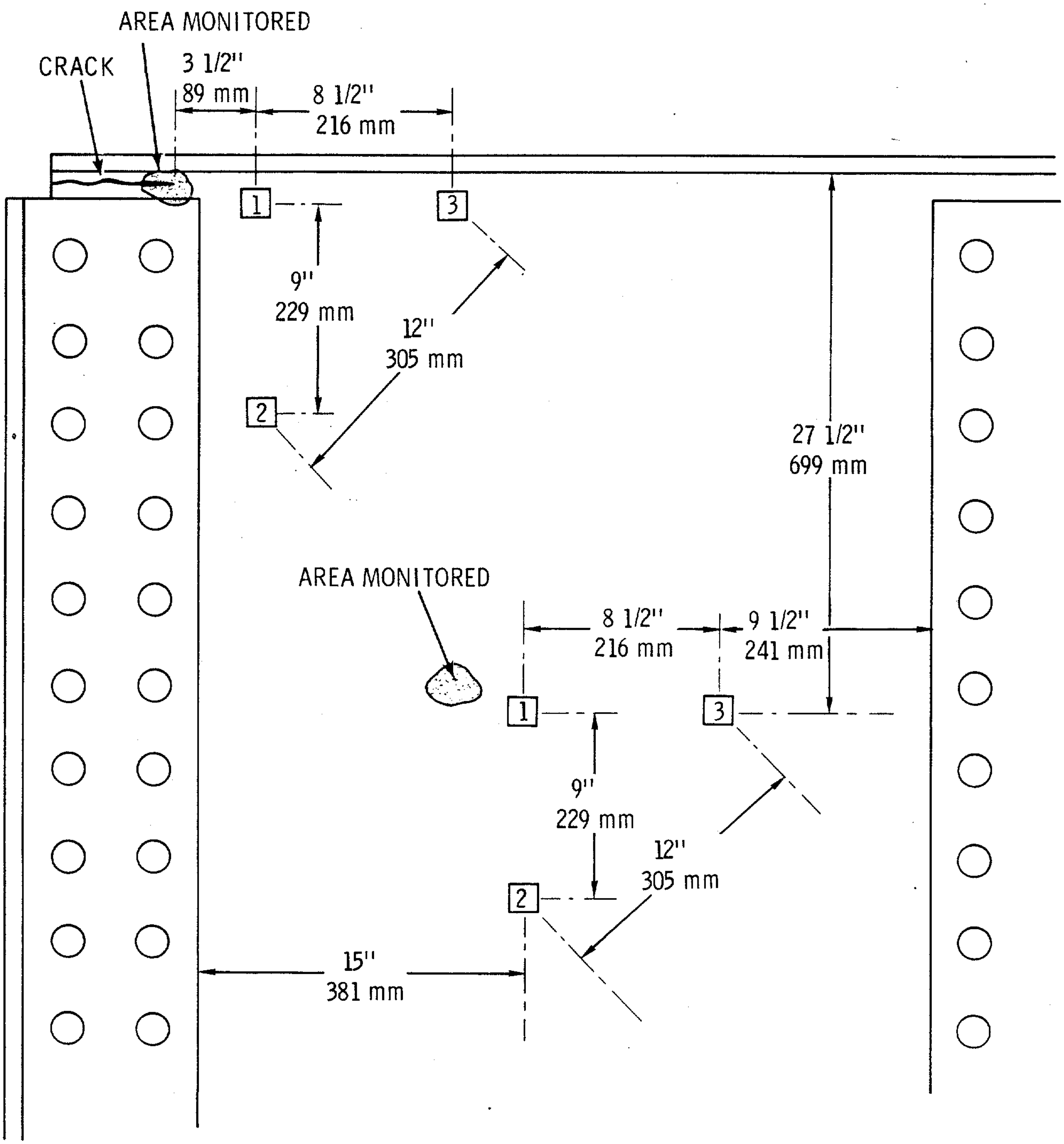


FIGURE 4
Test Arrangements, Toutle River Bridge, Floor Beam No. 6, 9/14-16/76.

DATA PROFILES - 3 HOUR UPDATE
TOUTLE RIVER BRIDGE TEST

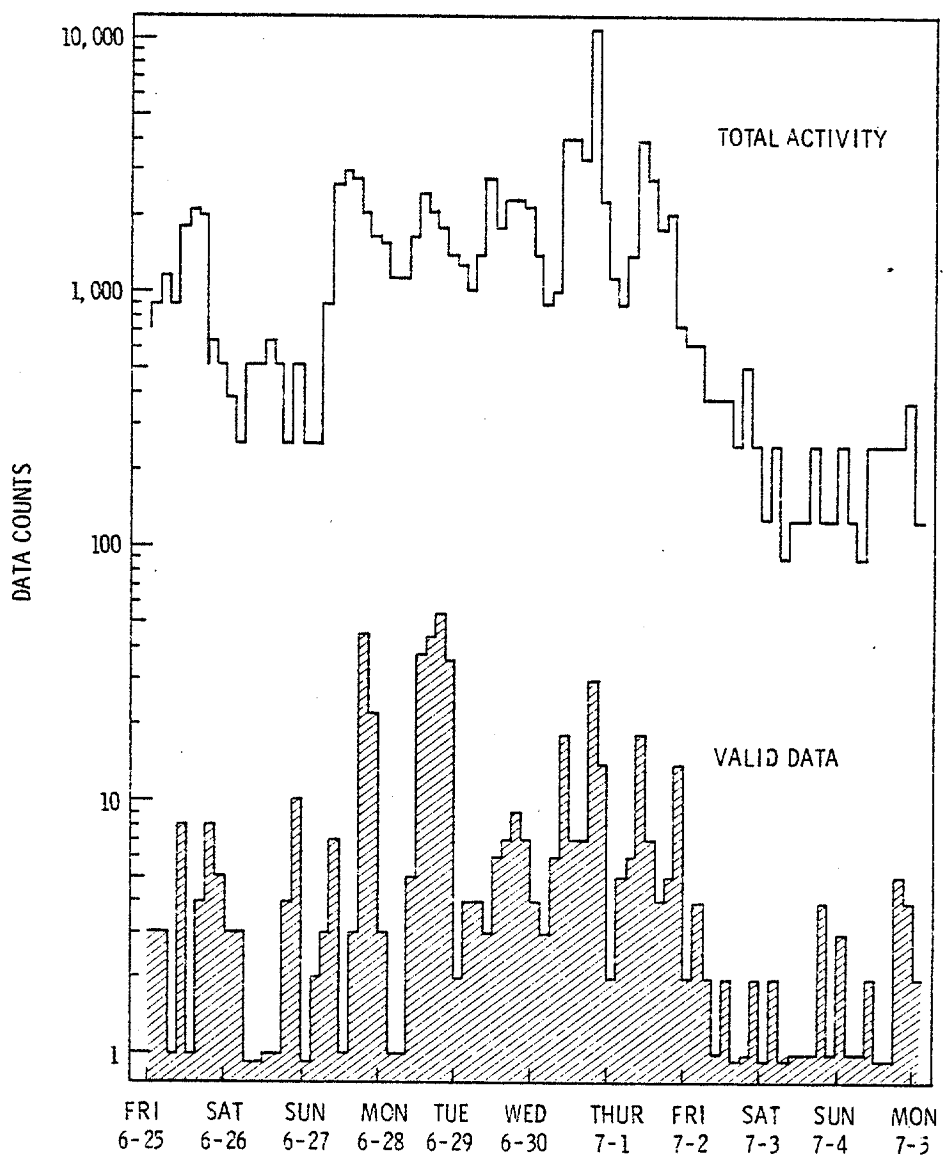


FIGURE 5. AE Data from 10 1/2 Day Test on Toutle River Bridge

seems like there is a relationship. We are not that sure that this data is valid.

Figure 6 shows a typical detail using the series mode. The crack is occurring up in here. Even though we can only mount the transducer in this area here.

This is Figure 7. Now I am going to talk about the magnetic field disturbance. We kind of neglected our pre-stressed concrete bridges and many reinforced concrete ones that we have in the system. So we have addressed that problem.

After going through a series of evaluations, we came up with a magnetic field method to look through the concrete, to look at the reinforcing steel rod in the concrete girder.

All we had to do was set up a cart that had a magnetic winding here. We have four Hall probes in this little box here which measure the disturbance from the field into the concrete.

(Slide) N.A.

The cart runs along a particular strand or rod. We just run on out 15 or 20 feet, wherever we want to go.

(Slide) N.A.

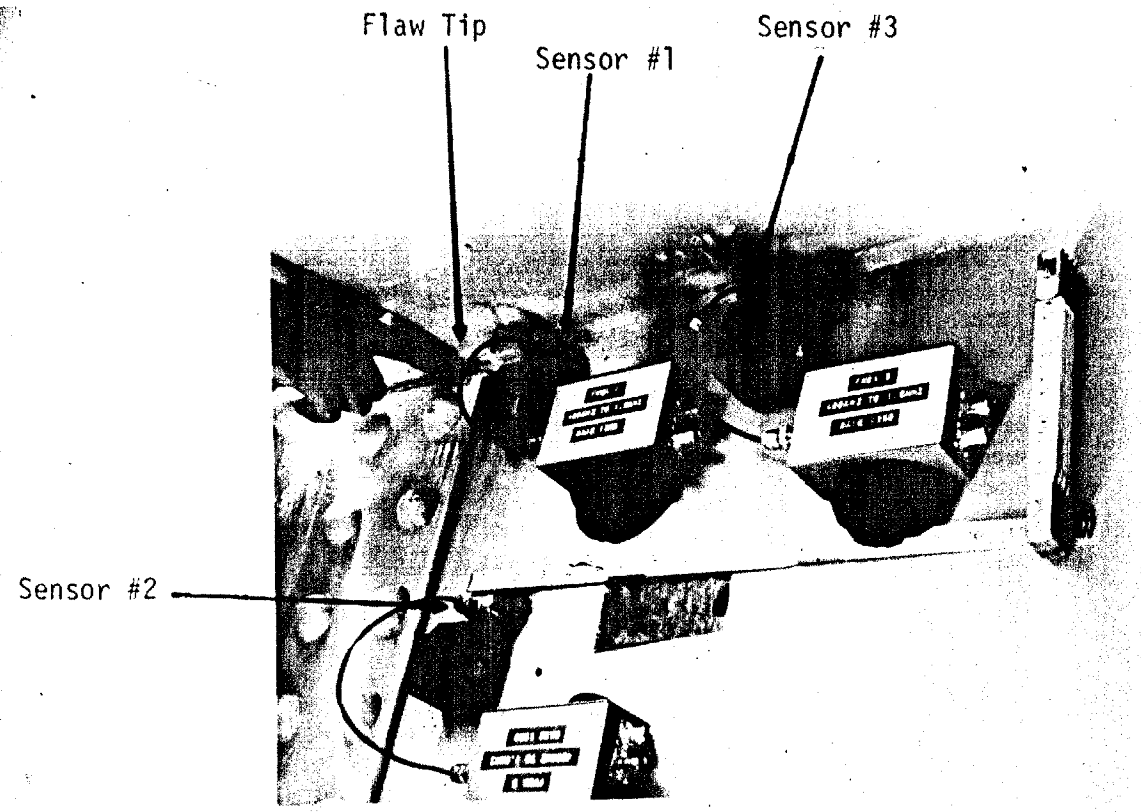
We have a test specimen. You can put in any number of strands in here. This is for simulating post tension members.

(Slide) N.A.

Here is an end view of it. It is about 20 feet length of a typical precast beam.

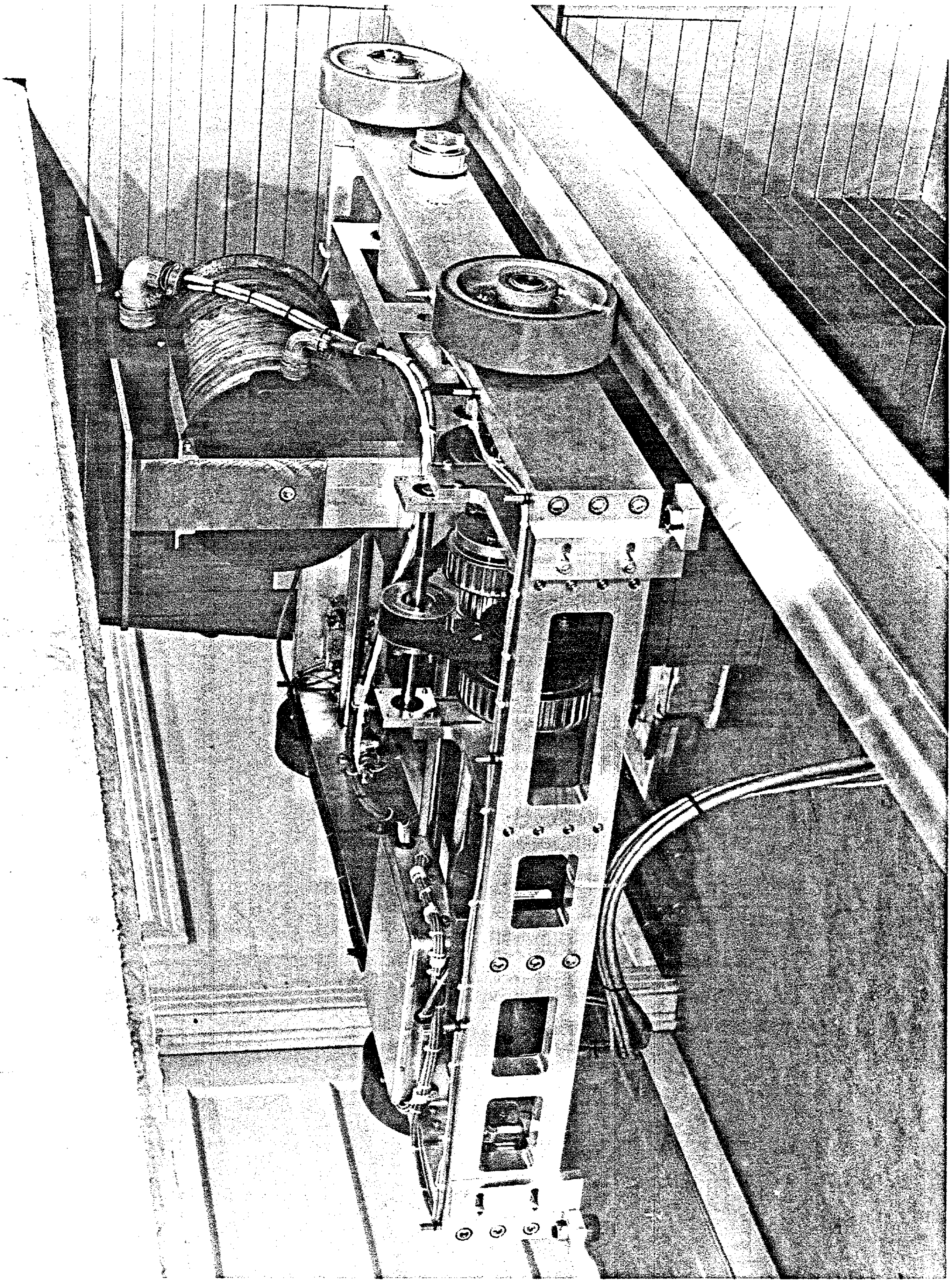
Figure 8 shows that we did a field test on a bridge out in Salt Lake City. This is an aqueduct -- viaduct actually -- through the city there. These are post tension members up here, only four rods to each girder. There were some 190 girders on this bridge. This is the set-up we made, just putting the rails up on hangars, rolling the instrumentation along the rails.

This is Figure 9. The cart goes like 15 feet a minute so it doesn't take very long. There's an umbilical coming down to control the instrumentation.



Sensor Placement with Respect to Flaw

FIGURE 6. AE Sensors Installed for Source Isolation of Floor Beam Crack - Toutle River Bridge



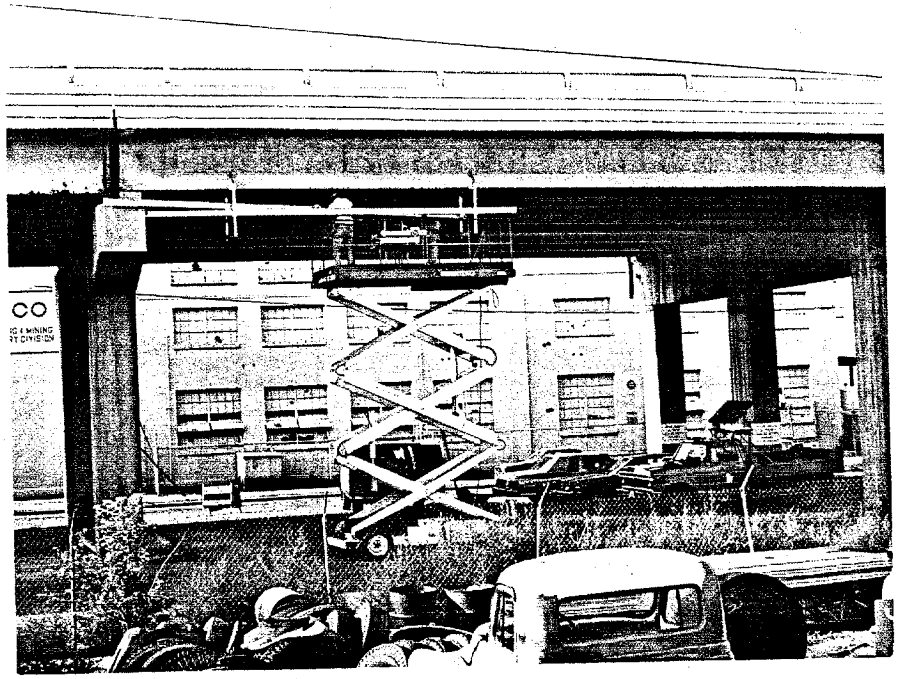


FIGURE 8

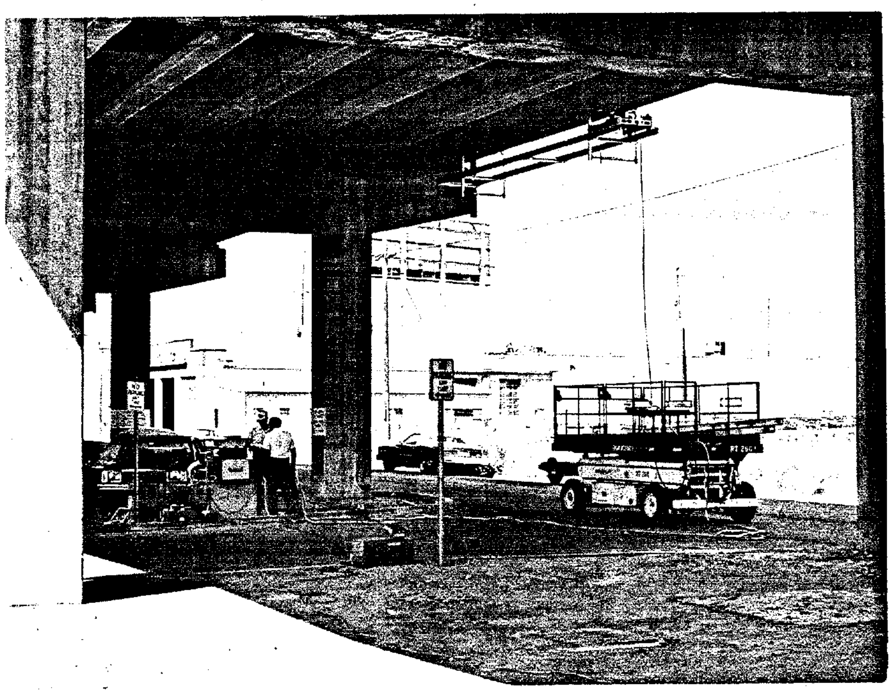


FIGURE 9

Figure 10 shows that this whole thing can be transported in this little van. The rail is on top and the instrumentation's inside. This is a little platform that we're able to move around and get in a position to hoist it up, and get it on the rails.

This is Figure 11. The instrumentation sits inside the van; here's the CRT, this is for the floppy disk, the console, the driving mechanism. It's pretty self-contained. All you need is a little Honda generator to power these. I don't think I've got a picture of that.

(Slide)

Now I'm going to get into another development we have called color tomography. You've probably heard about it since the CAT scanners have been in the hospitals. This is kind of a spinoff at the University of Texas of the medical application.

In this case here, they have a source over there, the platform for the specimen here, and the detector bank over here. We have sponsored this research, and it's just about ready to be completed on the 28th of next month.

This is Figure 12. We'll have a report on it -- what it is. This is the source; there's the detector bank. This is your specimen with a known flaw in it.

Figure 13 shows the actual structure, the section through the specimen.

Figure 14 shows the actual tomographic replica. This is the actual cut-through there through the section.

(Slide) N.A.

We want to look at welds. We aren't so much concerned about the wooden pilings as we were about our welds. Our big thing here is how can you use something like this on a bridge? It's very difficult to do a partial scan. You take a typical I-beam, you can't go around the body or something. Or a nice round hole, or even square, so you've got to think of some way to partially scan to do the weld, and also find us enough meaningful data to be able to tell if we do or do not have a crack in it.

Some of the slices are only mils thick, two or three mils. They can be seen very discretely, but how many can you afford to take?

FIGURE 10

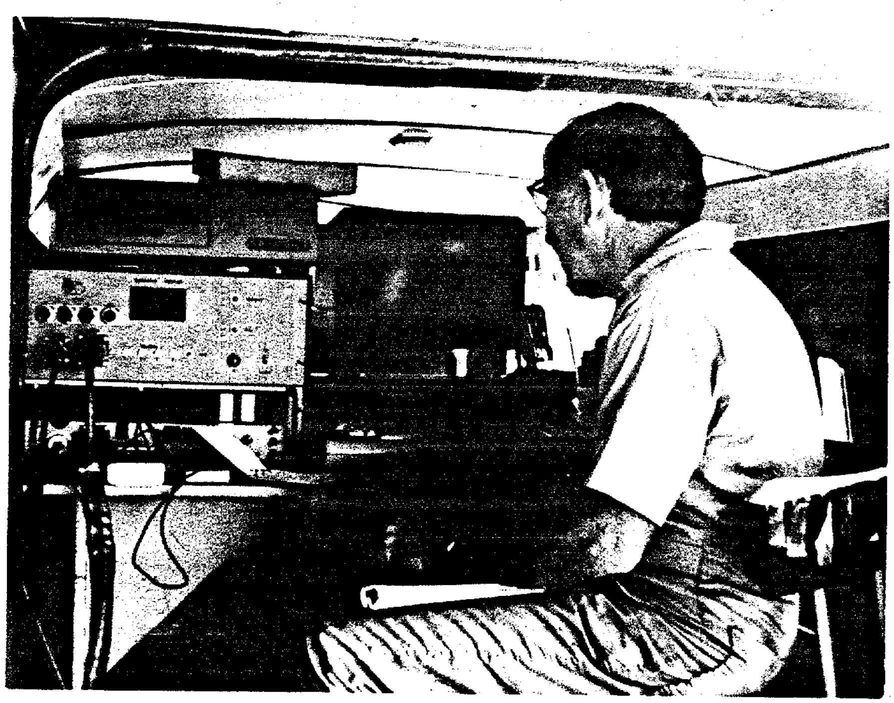


FIGURE 11

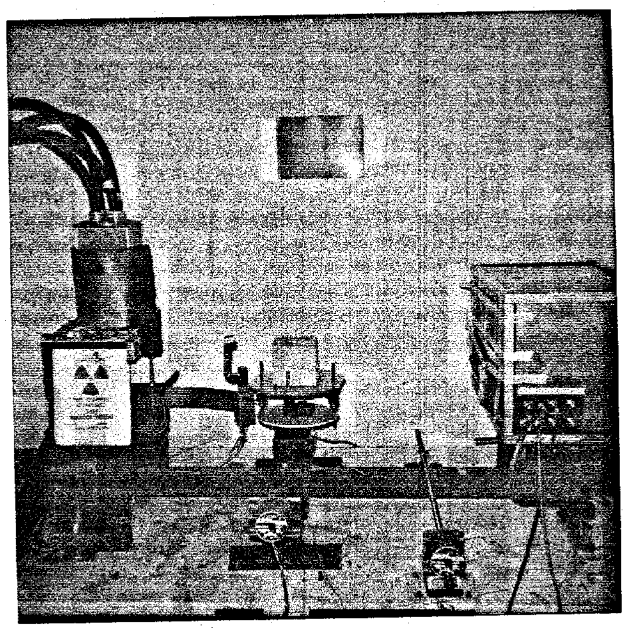


FIGURE 12

Laboratory Set-up for Photon Tomography System (a) Radiation source on left; (b) Specimen on Platform Center; (c) Detector Bank on right.

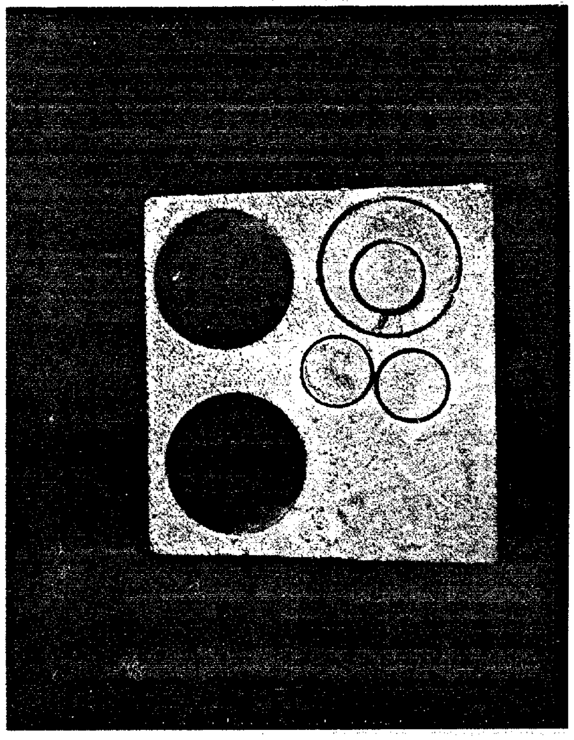


FIGURE 13

Concrete Block Specimen with Various Large Holes, Small Cuts, and Fractures.

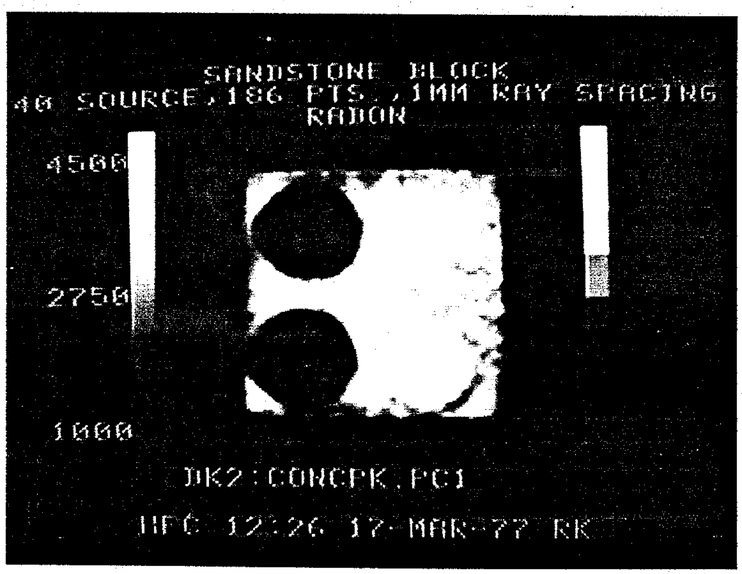


FIGURE 14

Photo tomography - Replica (Reconstruction) of Concrete Block Specimen.

This ~~is~~ Figure 15. Now I'd like to talk about the development of our residual stress measurement work. This is the Barkhausen unit that was developed at Southwest. This is the probe, of the Barkhausen unit, and this is the instrument for those of you unfamiliar with Barkhausen. It is only good for surface stresses.

This is Figure 16. In our contract, we asked for an in-depth measurement that would give us a stress gradient across some of these large members. These may in some way be 3 or 4 inches thick, and they were able to get through 2 inches of metal with the acoustic birefringence method -- that is, using the time of flight differences in orienting the shear wave, focusing exactly on that spot.

You need two readings in order to give an indication of any stress present. It's very questionable whether this is going to be applicable or not. As a matter of fact, I don't know that we are pursuing this any further, but in conjunction with some other method, it might have some merit.

At the present moment, it's not being funded any further. The equipment's available if anybody wants it and the instrumentation didn't really prove out to be that successful.

(Slide)

Next, I'd like to talk about in-process acoustic measurement of welds; we have a contract with Gard, Inc., in Niles, Illinois. That contract was complete after a four-year study on December 31. The report is coming in; I'll have it available for anybody who wants it.

They did a very good study, (Figure 17), but the instrumentation they advocate for us is this unit called the acoustic emission weld monitor. It's a three-channel system for monitoring in-process welds; in other words, they've been able to detect little cracks, or slag inclusions immediately in the weld process.

(Slide) N.A.

It's had some field application. The whole thing behind it, as I understand, is the way they treat AE data they get. You have to apply, a filter. It has to satisfy a certain rate criteria like 4 emissions per minute.

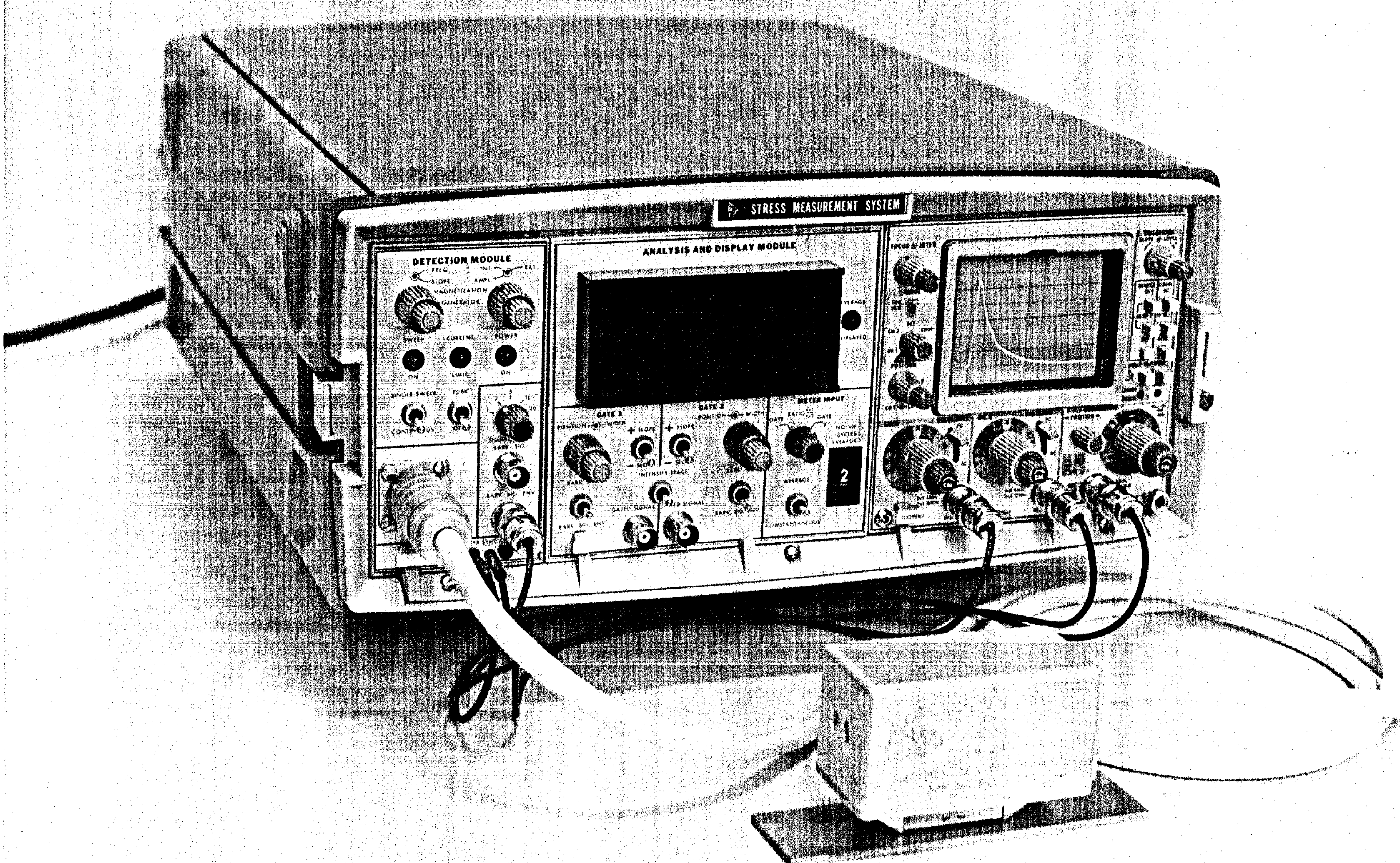
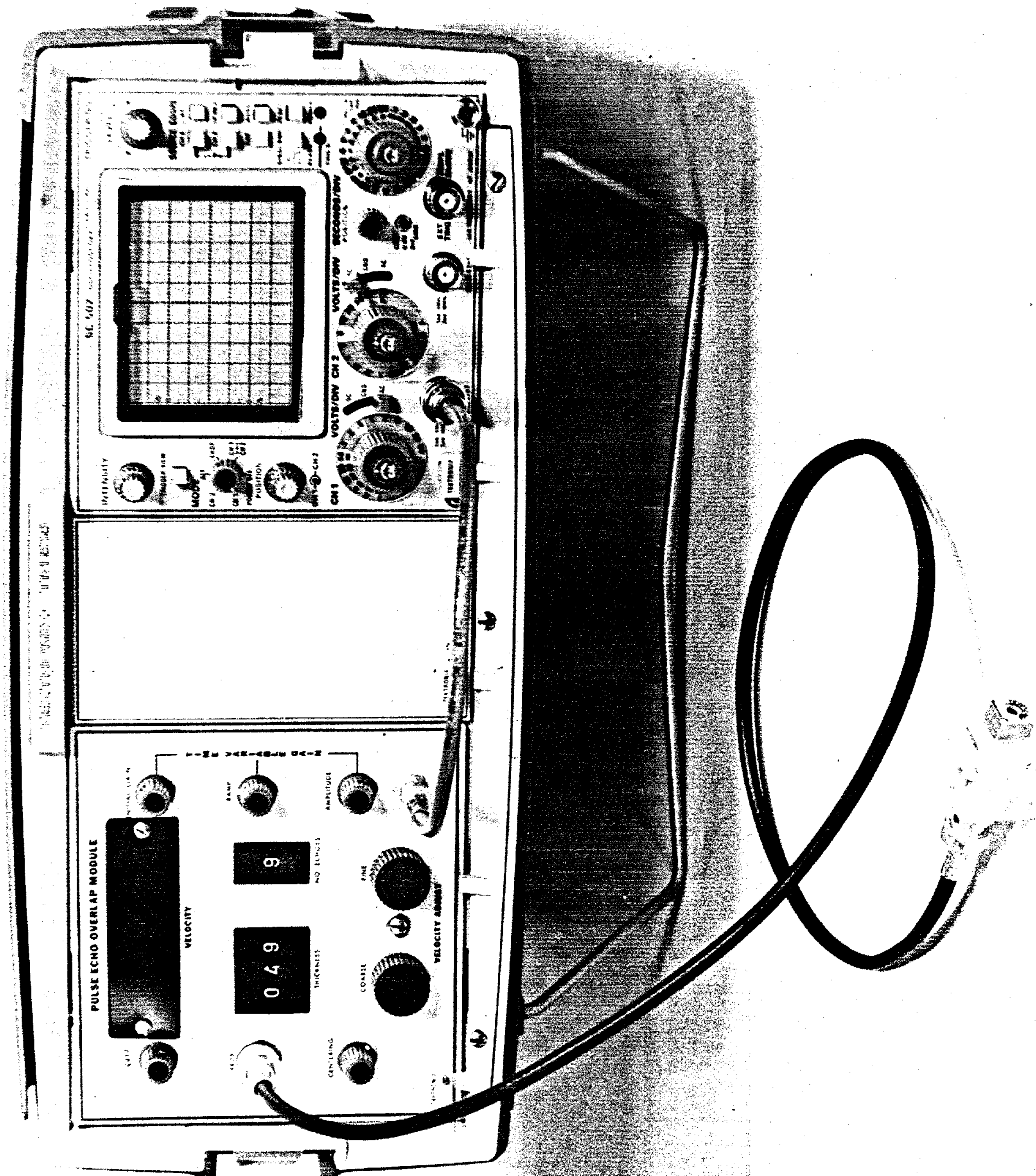

STRESS MEASUREMENT SYSTEM
DETECTION MODULE
ANALYSIS AND DISPLAY MODULE
METER INPUT
2

FIGURE 15


PULSE ECHO OVERLAP MODULE
VELOCITY
THICKNESS
NO. ECHOES
COARSE
FINE
VELOCITY ADJUST
CENTERING
RAMP
AMPLITUDE
VOLTS/DIV
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INTENSITY
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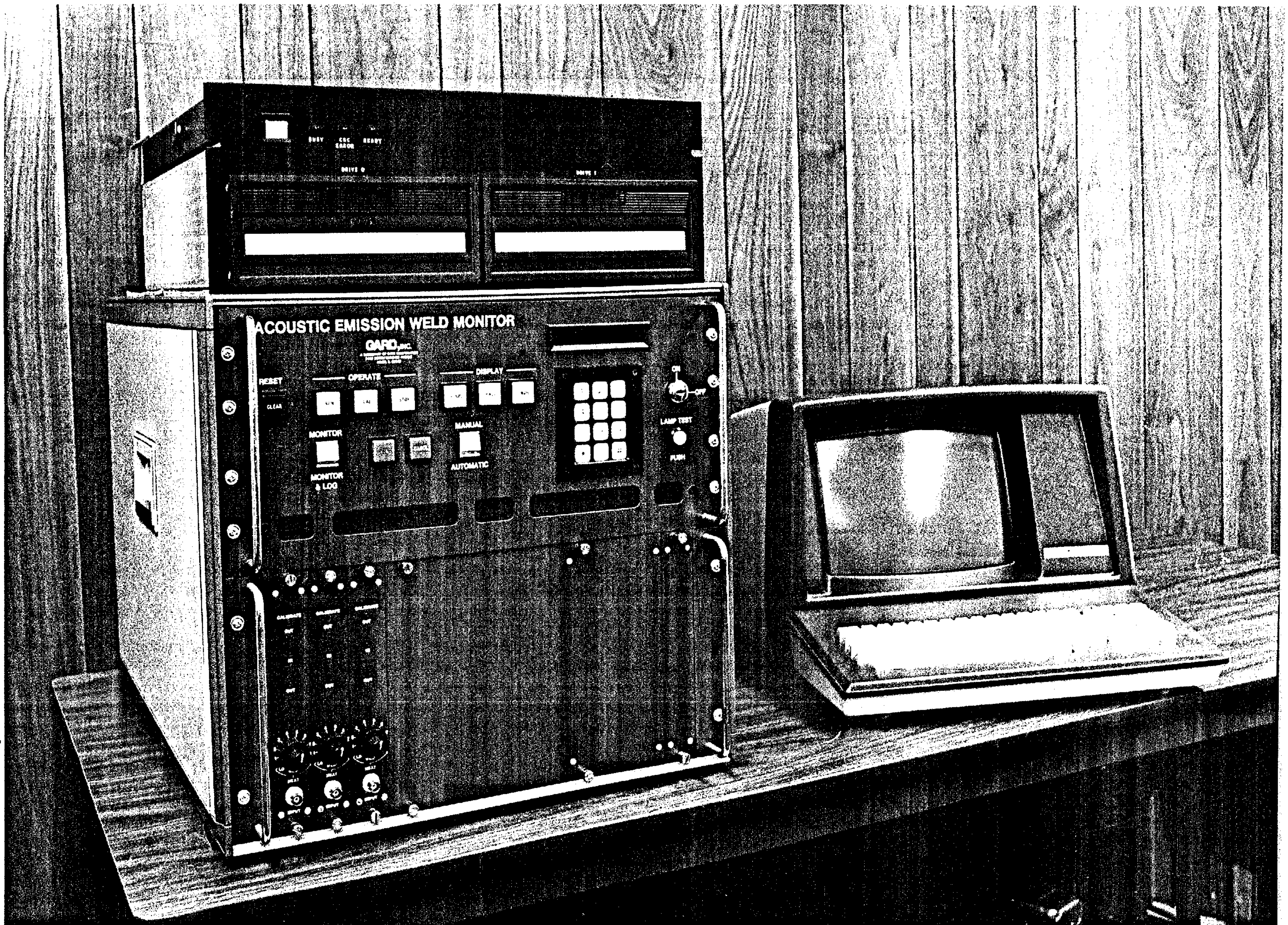


FIGURE 17

ACOUSTIC EMISSION WELD MONITOR (AEWM) DEVELOPED
FOR MONITORING IN-PROCESS WELD FABRICATION

Having passed the rate criterion, there's no problem there in locating where the event's coming from.

This is a linear array with two transmitters to pick up the location. It apparently is satisfactory in that particular application. I don't know how they characterize the particular flaw. How they can say "this is slag, this is cracked, this is a tightly bonded slag." They are able to detect 93 percent of the cracks.

Acoustic emission monitoring provides fixed sensor position, lack of sensitivity to the flaw position and orientation, and adaptability to computerization. Those are all true statements.

We also at this time are sponsoring a characterization of acoustic emission signals program. Dick Williams is the principal investigator. So far, it's only about six months in the program and he's made quite a bit of progress.

(Slide) N.A.

The goal is to develop an acoustic emission methodology capable of discriminating between detrimental and extraneous A.E. sources at bridge structures.

This is Figure 19. Dick Williams developed this acoustic emission sensor. He calls it the point-of-contact transducer. I have one were. It's a very discrete pick-up here at the point; that is the transducer, the point of the sensing head. The rest of it is housing. And it gives you some idea of the height and dimensions of it.

(Slide) N.A.

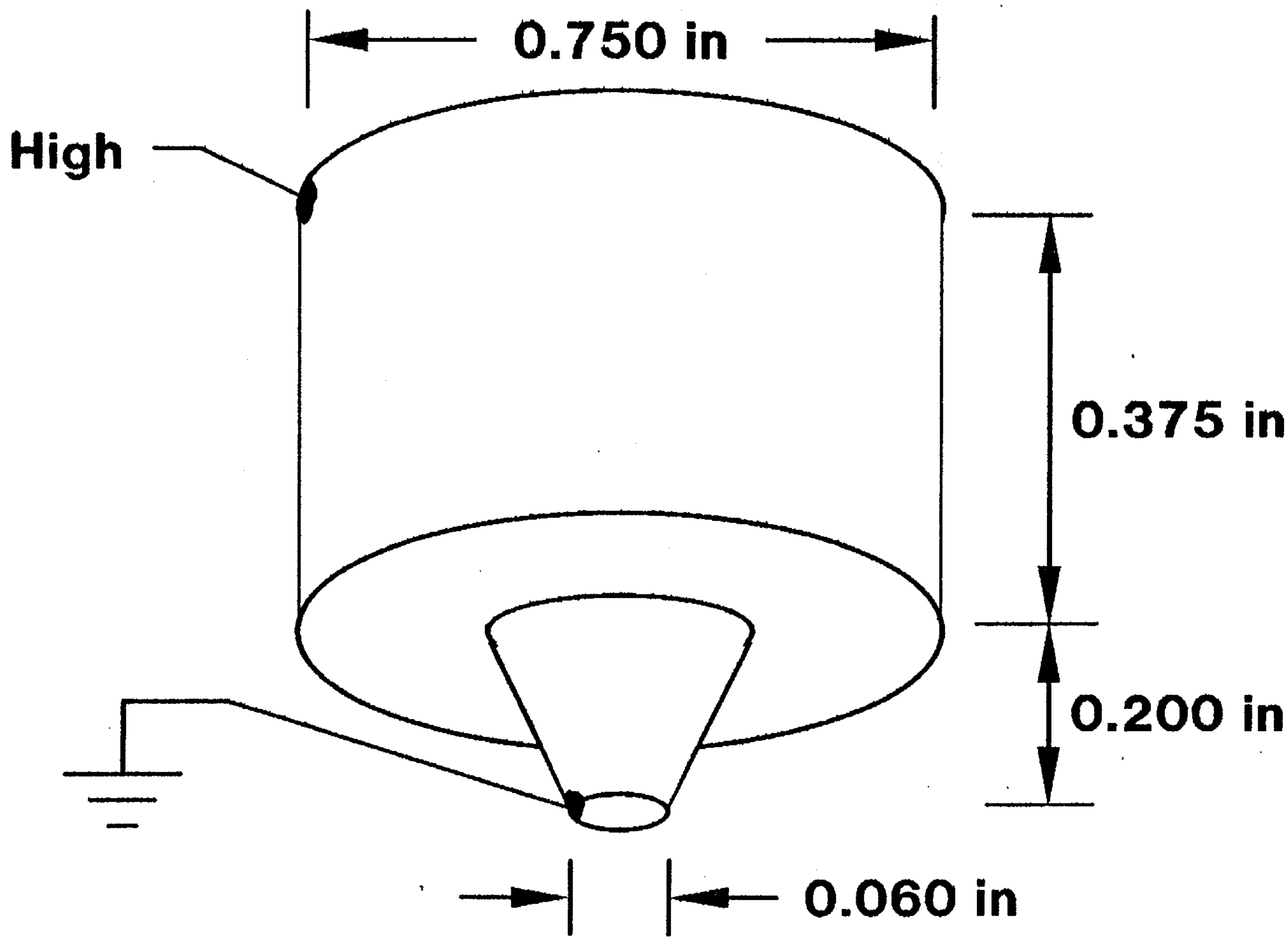
-- a film-type of transducer. I don't want to talk about it here now. It's the polyvinyl difluoride type which is commercially available, but it hasn't got the response.

There is a report coming out on that which should be due about the middle of the year. I'll be glad to supply you reports of all these programs if you'll just leave your name on that yellow sheet out there.

DR. RUBIN: I just wanted to point out that there's been a little work done at the Johnson Space Center, using a single-point-random-modal-test technology to detect failures. There was a paper published in the Shock and Vibrations bulletin in May of '82. They report the detection of some cracks in the shuttle-orbiter body flap

(Note: Text does not reference a Figure 18.)

PCT CONSTRUCTION



RA451TX.012

FIGURE 19

that had not been detected by conventional visual x-ray ultrasonic inspections. I have a paper here which you're welcome to look at.

Other work is going on in what we're hearing about here today.

MR. ALEA: That's by SDRC, isn't it?

DR. RUBIN: Right. SDRC is supporting this particular activity, this is traditional frequency response testing basically.

DR. BASDEKAS: Everybody more or less covered something related to using random time response data to detect changes in vibration frequencies and damping, and finally tried to program a mathematical model out of experimental data. Is it possible, somebody, to go this way? Or has it failed, and was it never considered, and if so, how come?

MR. COLE: Maybe just one thought on the problem. What scale of flaw are you trying to detect?

DR. BASDEKAS: I am not trying to detect a flaw; only whether I lost a member. The effect of stiffness of the member has been reduced drastically, whether somebody cut it, or it corroded.

MR. COLE: I think that's our basic problem; that is, if the flaw is just a tiny crack, then you get into one method up here, acoustic monitoring of some sort; if you get a large crack, maybe simpler techniques would work.

Our problem here is I think we are trying to get one method that covers all flaws, and that might not be possible.

MR. KNAPP: Knapp from Amoco Production Company. One of the problems, of course, is the large magnitude of loads.

All I know, it's very difficult to do load tests offshore, primarily because of the magnitude of the loads that we have to deal with. These are measuring loads in dynamic systems, with background noise. That's what a hundredth or a thousandth of what the structure was set up to resist.

We had a situation recently in the North Sea where they had nine-meter waves, and the stress response on the strain gauges was just above the threshold that was detectable.

DR. SUNDER: Probably we have stressed too much the technical capabilities of the different methods, and not really looked at it from a cost-benefit point of view.

If an oil company is really going to use one of these methods, the first question is: How much does it cost?

Dr. Joseph L. Rose
Drexel University

Long Wavelength Ultrasonic Inspection Principles for the Global Evaluation of Offshore Structures

DR. ROSE: I would like to review some of our recent work on offshore structural modeling and ultrasonic inspection from a paper that will appear shortly in the Society of Petroleum Engineering Journal, "An Ultrasonic Global Inspection Technique for an Offshore K-Joint."

Before going into details of performing ultrasonic evaluation, I would like to provide a bit of background on some of our work at Drexel University, and why we are involved in this particular problem, and how the global ultrasonic technique fits into our other research programs.

Ultrasonic testing was initiated somewhere around 1942. From 1942 to date, some 40 years, 95 percent of all work carried out in ultrasonic testing makes use of arrival time analysis, that is, measuring thickness of the part or a component by a pulse echo technique, determining the location of a particular reflector. Most work on arrival time analysis is used in thickness measurement and reflector location analysis.

More recently, though, in the last seven or eight years, people are trying to do more than just locate reflectors in an object, in a structure. They are trying to determine characteristics of that reflector. Is it sharp? Is it hot? That could be critical. Is it volumetric in nature? Perhaps we could leave it there forever. Is the stress concentration factor small?

So a great deal of work has been trying to establish flaw classification relationships and improve the economics and safety aspects of the inspection.

As a result of making use of the pulse shape information; that is, utilizing all information in the signal rather than just arrival time and amplitude, we have developed -- and several investigators are working on -- a feature-based methodology for reflector classification. A feature-based methodology makes use of physical modeling. In reality, we are using qualitative physics. We are looking at density function variations of signals, and so on.

When we talk about features of a wave form, we are referring to such items as rise time of a wave packet, pulse duration of the wave packet, etc., perhaps area under the power spectral density curve, perhaps divided into various segments, and so on.

We are making use of these features of an ultrasonic signal, and by recording all these features with a number of experiences, training information, knowing what really exists in a structure, we are able to develop algorithms and procedures to allow us to do signal classification, and hence make some determination of the critical or noncritical nature of a particular reflector.

In the feature-based methodology, models are important. As an example, we have developed some point scattering theories, back scattering techniques, mode conversion variations, to look at energy reflected from sharp tips of cracks, and so on; shear longitudinal energy absorption, particularly adhesive bonding of composite materials -- even in medical ultrasound if you have malignant and benign masses; layered media theory, their adhesive and cohesive character, and even recently looking at models of intergranular stress corrosion and cracking.

We actually model it as a multifaceted planar diamond and do the wave propogation calculations to find out what features change, and hence, try to develop classification algorithms.

Well, how does all this fit into the global ultrasonic inspection technique that we are talking about today? If we were to inspect a K-joint or offshore structure ultrasonically, with localized techniques that we have been developing to date for wells and OGSC's, it would take forever. You would have to scan unusual geometrics in the joint areas of the welds. It would be tremendously tedious to carry it out in detail. You wouldn't have an accurate description in your training base.

I might point out, five years from now it might be easier, because of robotic controls, and so on, to send this system down to automatically scan and record the data with computers and look for changes. So it might be easier in the future, but for now it is very tedious and complicated.

So what we would like to do instead is develop a global ultrasonic procedure. That is, let's flood the K-joint structure, the offshore structure with ultrasonic energy over as much of the structure as we can, and look for damage initiation, crack initiation, and we will correlate that damage initiation with some signal changes that we can record on an oscilloscope with a computer, and so on.

Hence, we are looking at a delta signal that has some correlation to the change or damage initiation. It turns out our feature-based methodology in the flaw classification work used earlier is still useful, because we want to try to estimate what kinds of changes in wave propagation might occur, so we can select features for use in our global inspection technique that might be even more sensitive to damage initiation, crack initiation, and so forth.

So all the earlier work that we have carried out is tied together, pointing toward this global inspection technique. The idea is now can we run a test, some complete tests I will discuss in a little while, and see if ultrasonically we can point out an early warning of failure of the structure. We have done this successfully. The only problem, perhaps, with the technique is, it is a little too sensitive. The warning is a little earlier than you wish, hence, pointing out the possible damage initiation or crack initiations in the structure a little too early.

As you know, it is possible that a K-joint can have a four - or five-inch crack in the structure for many years and not catastrophically fail, but ultrasonically, we have noticed that four- or five-inch crack. The question is, what do we do? Should we repair, further monitor, etc.,?

So we are using the feature-based methodology to develop a global inspection technique for a K-joint.

Before going through the details of the overlays, there's a few slides I would just like to show.

(Slide) N.A.

This is Mike Fuller, who will be talking a little bit later, using our ultrasonic transducer, sending energy around the circumference of the K-joint, running some calibration tests.

(Slide) N.A

This is the structure ready for testing, the hydraulic ram in here, from 10,000 pounds tension to zero, in a fatigue mode, causing failure to occur at this point in the structure.

DR. LIU: You are spreading the legs; is that what you are doing?

DR. ROSE: Yes. And cracks were carefully observed with dye penetrant testing at around 79,000 cycles.

(Slide) N.A.

Initially, we put clay to simulate barnacle growth on the structure, and it did, indeed, affect attenuation. There was a loss of the ultrasonic energy as it propagated around the structure, but no significant pulse shape changes, hence, no change in sensitivity.

MR. ALEA: Was that done in water or in air, Joe?

DR. ROSE: Yes it was in water and in the air also. We ran several comparisons.

This is Figure 1. Let's now go through details of the test. On this we used a microprocessor-based inspection for tubular joints. Our work, under the sponsorship of ONR, is related to microprocessor development in ultrasonics, tied together with USGS Minerals Management. We tied microprocessor technology and ultrasonics together with the offshore structural inspection in this particular project, and we used an ultrasonic transducer at one end of the K-joint. It floods energy around the structure, and we use a receiver on the far side.

We are using a through-transmission procedure. Through-transmissions seem to work reasonably well. We used a pulser in this case a kb 6000, computer control flaw detector unit, a microprocessor LSI 1123. You will see later a very small portable unit for collecting data. Data was collected with a Biomation 8100 analog to digital converter, 100 mH-2, to carry out the power spectral density analysis; and for data storage, a dual floppy unit, recording oscilloscope, and so on.

So we used this microprocessor-based system, portable, easily carried from one lab installation to another, to collect data and do real-time analysis.

In fact, on the last fatigue test, we did real-time analysis, made predictions on-site, plotted similarity measurements, and were able to monitor changes in damage initiation.

Figure 2 shows a little more detail of the shoe assembly. Ultrasonic waves are sent through this wedge material, and by refraction, ultrasonic energy is sent into the tubular structure and it is received at this point.

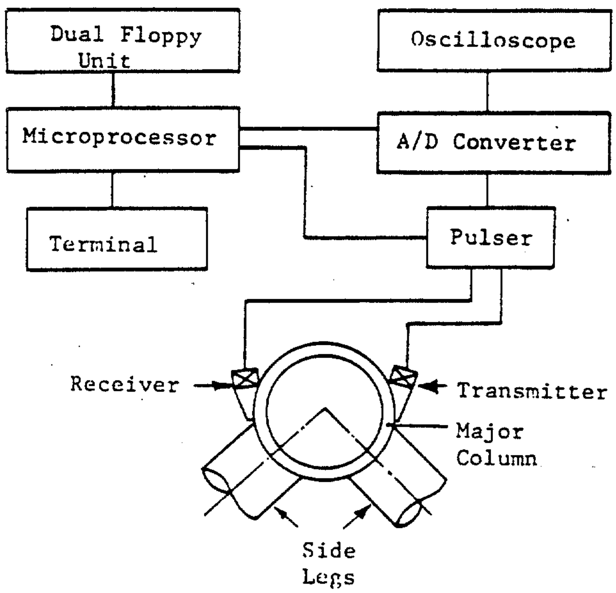


Fig. 1—Microprocessor-based inspection system for tubular joints.

FIGURE 1

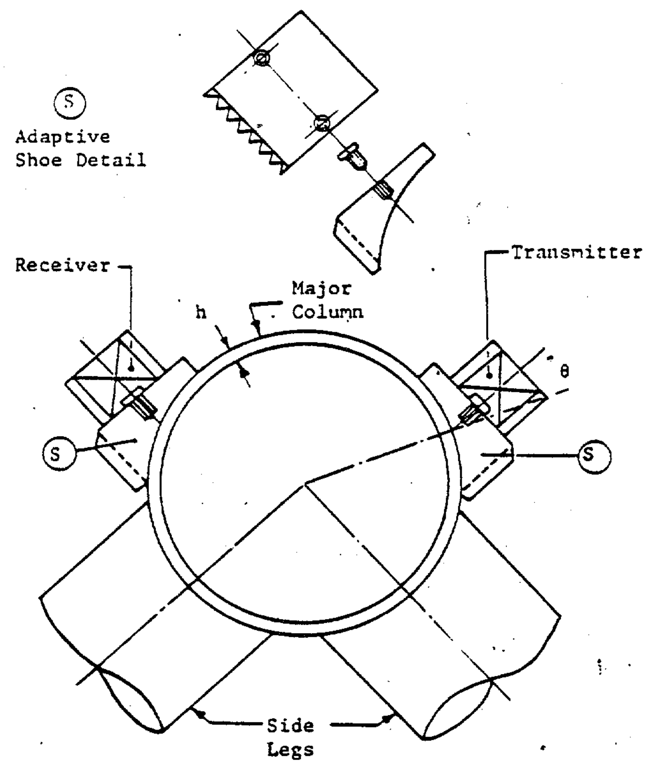


Fig. 2—Transducer configuration for global inspection system.

FIGURE 2

The frequency to thickness ratio was a critical parameter, as well as the angle of incidence, the refraction angle into the structure is important, in order to get complete coverage of the ultrasonic waves, as they travel through the tubular structure.

Figure 3. In fact, to demonstrate the idea of diffuse coverage, if you look at this diagram, if too high a frequency is used, you get have very strong directivity and incomplete coverage of the structure. So you are missing areas that are not being inspected at all with the higher frequency. As you go to some intermediate frequency range, what happens, because of destructive interference phenomena, you get a very messy situation. If the incident angle and frequency-to-thickness ratio is not conductive to lamb-wave formation in the structure as it is here; if everything is superimposed correctly, you produce a lamb wave in the structure, giving us complete coverage.

You get a new group velocity, different than the original shear wave velocity, from which we can extract data and carry out our analysis. So we are trying to get a nicely behaved wave form in the structure, with maximum energy in one mode, so we can extract our data in a reasonable fashion.

Let's look at Figure 4 for a moment, at some typical data sets:

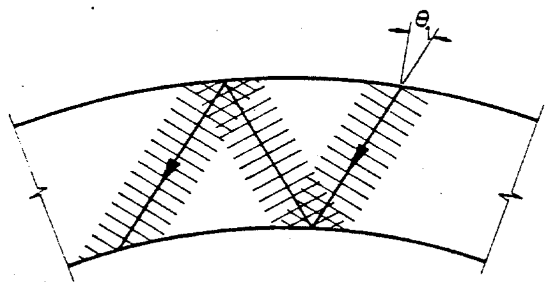
A. Ultrasonic wave form obtained from the nondamaged joint;

B. Ultrasonic wave form from a structural joint with damage.

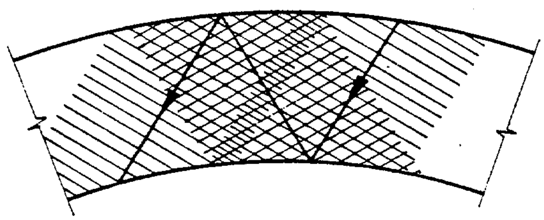
And, as you might guess, I am trying to show you that you really can't draw any conclusions on these two amplitude time wave forms. If you run hundreds of these, they will start overlapping. So time domain doesn't work too well.

We, therefore, carried our work out in the Fourier transform, using power spectral density measurements. By using power spectral density, we eliminated amplitude as a factor, as well as the variations at arrival time, and we look at the content as a function of frequency.

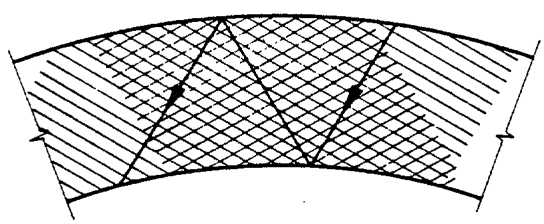
Figure 5. In working with the power spectral density -- for a second, I would just like to focus on this one equation -- we used for the similarity measure. There are many which



Traditional high-frequency ultrasonic wave propagation.

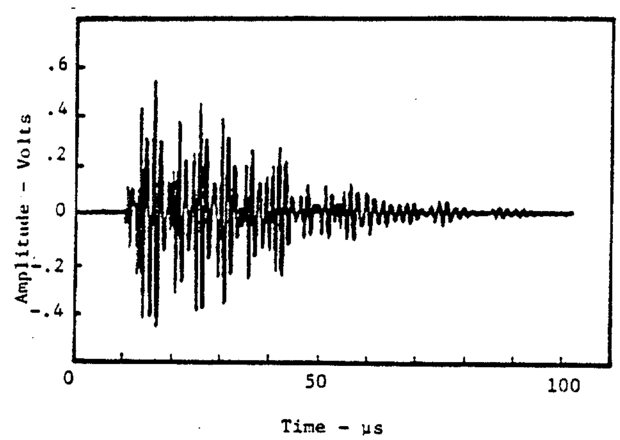


Unfavorable interference at low frequency resulting from improper value of θ_1.

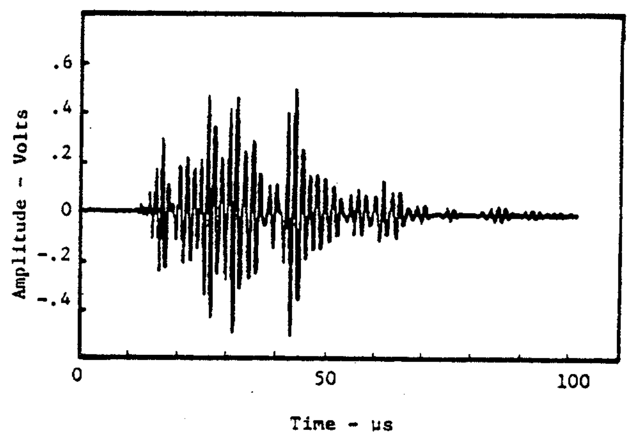


Lamb-wave propagation resulting from favorable interferences of reflecting wave fronts (proper choice of θ_1).

FIGURE 3



Ultrasonic waveform obtained from undamaged joint.



Ultrasonic waveform obtained from joint after sustaining damage.

FIGURE 4

Consider a signal given by f(t) and a second by f($t-T$) where T is the phase shift. This is the ideal case when the signals are identical but displaced in time relative to each other. Taking the Fourier transform of each gives

$$\mathfrak{F}[f(t-T)] = e^{-j\omega T}F(\omega) \quad \text{(3)}$$

and

$$\mathfrak{F}[f(t)] = F(\omega). \quad \text{(4)}$$

Now the power spectrum of each is given by $|F(\omega)|^2$, since

$$[e^{-j\omega T}F(\omega)] \times [e^{j\omega T}F(\omega)^*] = |F(\omega)|^2. \quad \text{(5)}$$

Thus the power spectra are identical, and the effects of the time delay are removed.

The formulation of the similarity coefficient is given as follows.[10]

$$s(\vec{x}, \vec{y}) = \frac{\vec{x}^t\vec{y}}{\vec{x}^t\vec{x} + \vec{y}^t\vec{y} - \vec{x}^t\vec{y}}, \quad \text{(6)}$$

where

$\vec{x}$ = a digital representation of a reference (before damage) ultrasonic waveform (a vector),

$\vec{y}$ = a digital representation of an ultrasonic waveform obtained for comparison (a vector),

t = the vector transpose, and

$s(\vec{x}, \vec{y})$ = the similarity coefficient between the two vectors x and y.

FIGURE 5

exist in the textbooks on signal processing and pattern recognition. This one is taken from Duda & Hart. In this equation Y is a reference spectrum, X is the unknown.

Really, what we are doing now is comparing power spectral density of a reference, undamaged state to new data as it comes in. We are using the coordinates of the power spectral density in the neighborhood of .8 megahertz center frequency, and a total 1 megahertz band width.

We looked at the total similarity measurements over the total range, and also divide it into four quarters to find out where the maximum sensitivity might be with respect to a particular frequency range for depicting crack propagation in the structure.

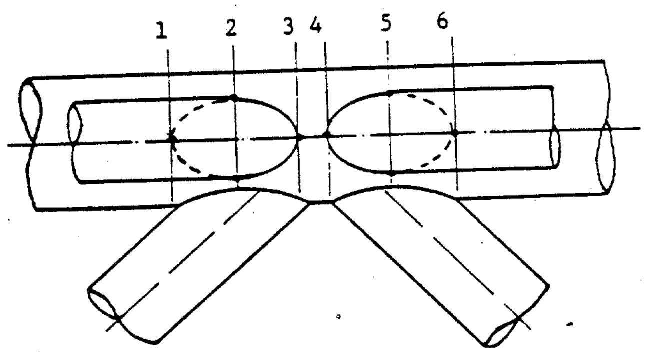
Figure 6. This figure points out the history of all these things, we did some work initially on a 1/19 scale model, where we changed different frequencies, angle of incidence, in order to understand the penetration problem, the resolution problem, the lamb wave propagation problem, and so on.

We put a number of drill holes at various positions with different sizes to do some sensitivity analysis, to see if we could, indeed, detect these small holes by using this global inspection technique with the similarity measure just discussed. So initially, we worked on a 1/19th scale model.

Figure 7. Later, we used a 1/10 scale. Changing scales is useful for looking at the wavelength, the thickness modeling, if you will, to see if it has been scaled correctly.

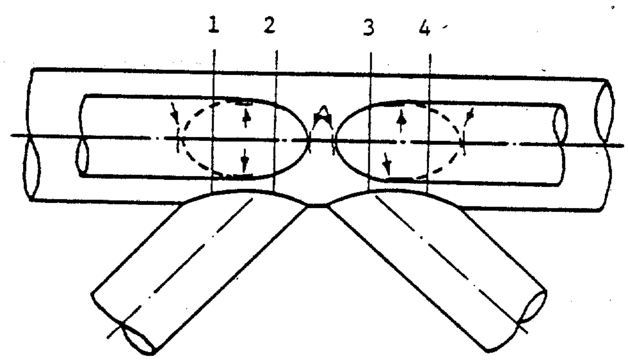
It is also important, because if we extend this technology from 1/3 scale model to full structure, we have to know what parameters to work with. So we did, indeed, gather some very valuable information. With the 1/10 scale model, we put saw cuts in at various positions, again, gaining some confidence in the technique, the global inspection technique similarity measure.

Figure 8. This is the 1/3 scale model of a K-joint -- these tests were run about a year ago, and more recently, we ran some tests on a one-third scale model to see if we could detect the cracks. I mentioned earlier there is a dye penetrant indication.



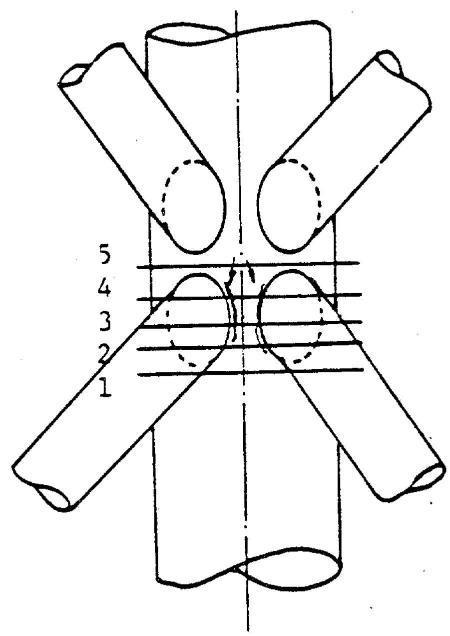
Data acquisition locations for 1/19-scale model testing; • indicates damages induced by side-drilled holes.

FIGURE 6



Data acquisition locations for 1/10-scale model testing; arrows denote damage induced by saw cuts.

FIGURE 7



Data acquisition locations for 1/3-scale model K-joint; arrows indicate damage.

FIGURE 8

Figure 10. Looking at amplitude, versus time, frequency, and power spectral density, it turns out that the similarity coefficient in this case is .658.

Anything starting around 1 to 9, because of the variations in noise is undamaged. You can see slight differences. But again, it is difficult to make a visual observation of changes in the power spectral density. But by using the analog to digital converter, then collecting the data, and the computer performing the analysis and coming up with a similarity coefficient, we have an objective evaluation of the signal change.

DR. GREEN: Joe, I don't know why you say that you have difficulty in the time domain. It is very easy for me to see the difference in those.

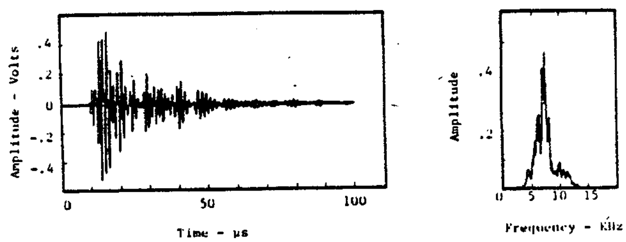
DR. ROSE: If I put 100 signals here of no damage and 100 signals of damage, they start overlapping. These are just two typicals.

It is interesting, Bob, we have done so much work with specimens, where the first 3, 4, 8 runs looked terrific. But then you get to 100, everything falls apart.

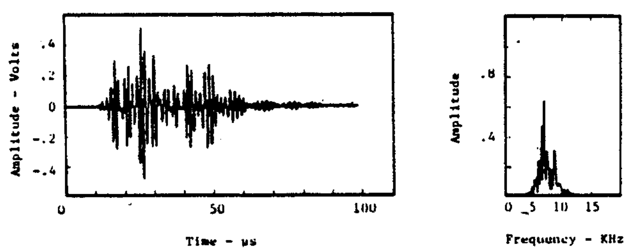
But this is holding together because of the computer objectivity.

Figure 11. This is included in the report, just pointing out again the .954 and the .638 -- no damage, some damage from cracks.

(Note: Text makes no reference to a Figure 9)

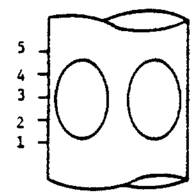
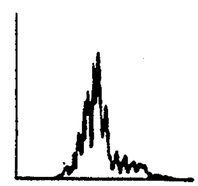
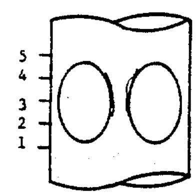
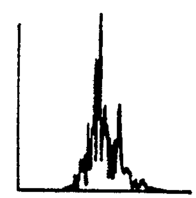


Ultrasonic waveform and its power spectrum obtained from 1/3-scale mode K-joint containing no damage.



Ultrasonic waveform and its power spectrum obtained from 1/3-scale model K-joint after sustaining substantial damage. The value of the similarity coefficient for these signals is 0.658.

FIGURE 10

Damage Status	Visual Identification	Crack Length (mm)		Power Spectrum†	Overall Similarity†
		Left	Right		
A*,		0	0		.954
B**,		254	279		.638

*No damage.

**Damage, crack detected 100% through major column thickness on right side.

†These data from Transducer Position 4.

Damage status for 1/3-scale model K-joint.

FIGURE 11

The ultrasonic technique located cracking. The cracks were up to around 4 inches -- but surface cracking, -- not penetrating very deeply. The cracking in the structure occurred at around 79,000 cycles.

DR. LIU: How do you know whether the crack is completely penetrated through the thickness? You said it was only a surface crack. How do you know? How can you verify it during the inspection?

DR. ROSE: We monitored it with a dye penetrant inspection. The dye penetrant technique, of course, only detects the crack. So, we are constantly running penetrant in for so many cycles, noticing nothing.

Finally, there is some small indication. And you can see there are very fine lines.

As the test continues, the lines get heavier as there is more penetrant and so on.

So, this is a qualitative observation. We did though move in with ultrasonics, not in too much detail, to look at the reflection in the cracks and could, indeed, tell it is growing.

So it was, indeed, confirmed that it started on the surface and eventually propagated through the structure. And as it propagated through the structure, of course, cutting through the wall, the technique, of course, becomes very sensitive. But we did notice it very early. As I said, perhaps it was too sensitive.

There are a lot of slides in this report where I go into detail, but I don't think I should go into all the details.

Figure 12. Now, to point out various transducer locations around the structure -- three and four worked best, because they were directly in line with the cracks.

And you can see that -- undamaged, damaged -- undamaged, damaged.

It doesn't hurt to monitor them all, by the way, because no crack is noted under location one, nothing under location two; there is a crack under three, crack under four, and nothing under five.

There is some beam spreading and so on. But it is pretty much directed around the structure.

TABLE 1—SIMILARITY COEFFICIENT ANALYSIS FOR ⅓-SCALE K-JOINT MODEL

Transducer Location	Damage Status	Similarity Coefficient: Overall	Spectral Quarter 1	Spectral Quarter 2	Spectral Quarter 3	Spectral Quarter 4
1	A	0.943	0.885	0.955	0.957	0.982
1	B	0.924	0.881	0.935	0.968	0.543
2	A	0.973	0.941	0.981	0.972	0.921
2	B	0.947	0.895	0.963	0.930	0.498
3	A	0.912	0.829	0.953	0.720	0.646
3	B	0.667	0.549	0.740	0.503	0.260
4	A	0.954	0.874	0.968	0.934	0.988
4	B	0.638	0.831	0.597	0.701	0.246
5	A	0.958	0.958	0.960	0.955	0.916
5	B	0.859	0.775	0.886	0.839	0.408

FIGURE 12

And looking at the spectral quarter with the emission here at .8 megahertz, we found the maximum sensitivity to be in the second quarter.

In fact, some of the other reference states -- looking at all these numbers, there are a number of comparisons that could be made. But if we stick with transducer locations three and four and analyze the second quarter, which we found from our earlier work, we get a very sensitive indication of damage initiation in the structure.

DR. SUNDER: Were all these transducers located around the same region of the damage?

DR. ROSE: Transducer 1, 2, 3, 4, 5, as we move across the structure, in various locations.

VOICE: How many welds did they inspect? You have six legs here. How many legs do you have here that you actually inspected?

DR. ROSE: Two legs and the main structure.

VOICE: And they were completely illuminated. So, it took five transducers.

DR. ROSE: Well, two transducers. And we moved them. In field practice, they would be permanently installed.

VOICE: How many would it take to interrogate two welds?

DR. ROSE: Four transducers, two senders, two receivers, in positions 3 and 4, because the edges -- the center portion, if you eliminate that area --

VOICE: But if you had 40 joints, it would take 40 times 2, or 80.

DR. ROSE: As far as implementation is concerned,it is difficult.

We can pick out the critical areas to monitor and develop inexpensive techniques to build these things.

In fact, we have in mind, later, having a pulser and receiver mounted right here. And by telemetry, we send it up. And we can constantly monitor daily or weekly, or whatever.

There has been a lot of price reduction work that has to be done.

Figure 13. In fact, this figure answers the question -- you are looking at 1, 2, 3, 4, 5.

DR. SUNDER: Certainly, in a sense, you are able to locate the position of the crack?

DR. ROSE: Yes.

Figure 14 shows the test instrument, by the way -- this is a KB-6000 flaw detector. These are where the floppy disks are stored.

And this is the computer, very small and compact. It is just amazing. An equivalent computer when I went to school years ago -- would fill this entire room.

And the analog to digital converter and the observation oscilloscope.

This is the instrument package. It is pretty reasonable to carry it.

This is Figure 15. The load spectrum for this last test was something like this, a fairly constant number of cycles. I guess that was over a two-week period that this test was run.

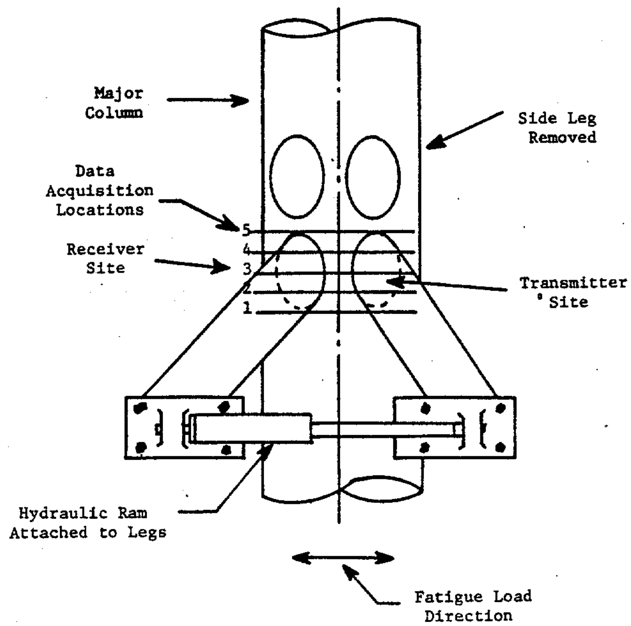
But anyway, cracks observed were somewhere in here, 79,000 cycles. The first ultrasonic detection was somewhere over here. It may be too early, so there is some work to be done. We have to come up with something not quite as sensitive.

DR. SUNDER: Why are you saying that this should not be early-warning sensitive?

DR. ROSE: Because the life of these things could be 10 years. And if we have early warning at five years, should we repair the structure at that point or replace it?

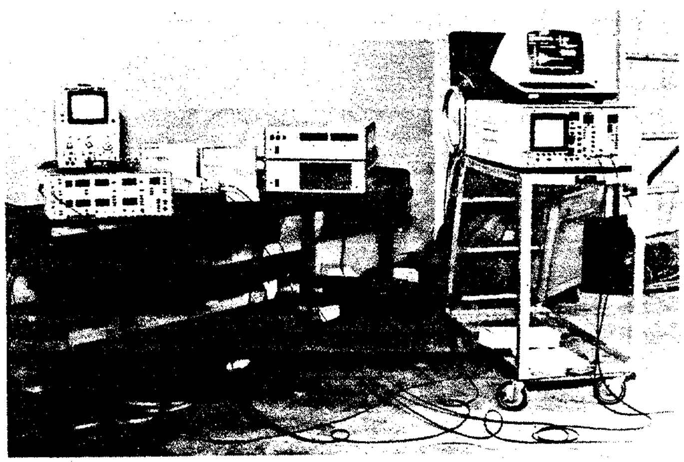
DR. SUNDER: It still indicates the thickness of the structure.

DR. ROSE: Yes. Like I said though, we can refine it. We don't have to, at that point, stop our tests.



Fatigue test configuration for 1/3 scale K-joint model.

FIGURE 13



Ultrasonic data acquisition and analysis equipment. (Note transducers in the foreground.)

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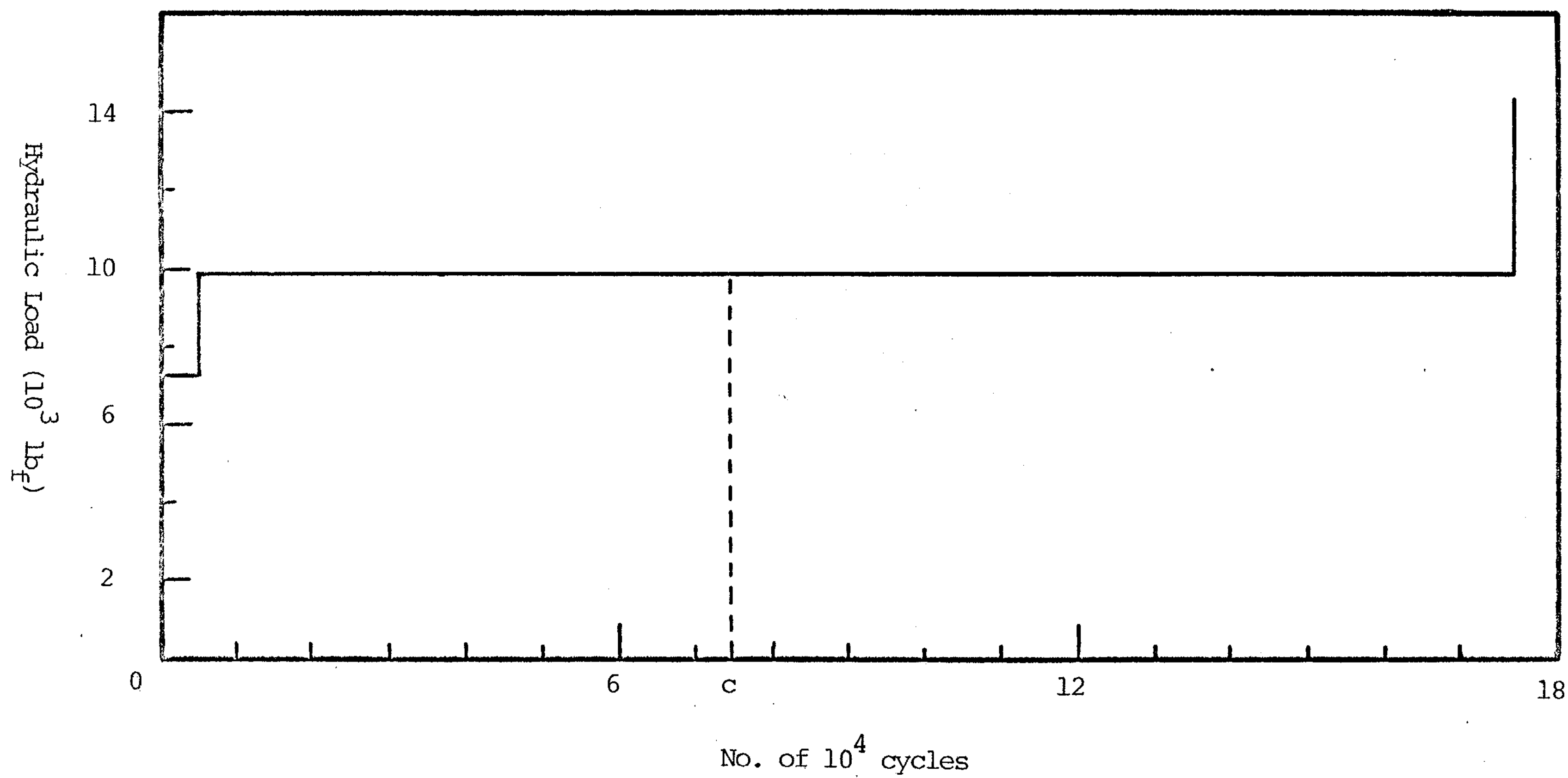
FIGURE 14

FIGURE 15



Hydraulic Load Pattern During Fatigue Test of 1/3 scale K-joint mode. Note: c is the crack initiation.

FIGURE 15

In fact, by changing the frequency range, going to lower frequency, we could probably move the warning out further, because we would miss the smaller cracks.

So, you have a nice laboratory study, but it needs a lot of work before you can put it into the field in an economically efficient manner.

Figure 18. This shows that there are some interesting curves, plotting our similarity coefficient. And in this case, over all four quarters of the power spectrum density curve variation, here is where cracking really started to occur. And you get the change somewhere in here, and it drops off. We used the two-point moving average.

DR. ROSE: This first quarter similarity measure is insensitive. Third quarter, not bad. Fourth quarter, questionable.

So, these are the fine-tuning elements in the procedure, the algorithms that might work best. Certainly it works reasonably well. Now, that was transducer location Number 3.

Figure 19 shows four similar observations made in the welded structure.

Figure 17 shows that we kept track of the various cycles, 37,000, 79,000 and 102,000, and plotted similarity measurements.

For these small cracks, the similarity coefficient hasn't changed yet. As they get bigger, you would drop off. You put in dye penetrant to track propagation.

VOICE: What are the size of those things?

DR. ROSE: In length? There are four to five inches.

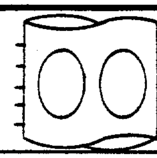
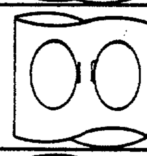
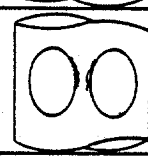
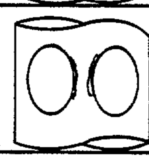
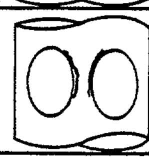
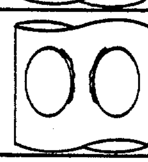
If somebody is interested in the reports, I will discuss it in more detail the variations in the different locations, as well as the number of cycles, variations, what all the numbers mean.

Figure 20. It is a fairly simple concept.

This is the sender transducer. And this is a receiver. Only five receivers will work. One won't work. For the signals received in these positions, obviously, the sender or receiver across the structure, this works the best. You

(Note: Text does not reference a Figure 16.)

Damage Status of 1/3 Scale Model K-joint Fatigue Test at NASA Goddard.

Data Point	No. of Cycles	Visual Indication	Crack Length (mm) Left	Crack Length (mm) Right	Overall* Similarity
1	37,000		0	0	.912
2	79,000		102	127	.925
3	102,000		165	197	.748
4	116,000		184	241	.737
5	126,000		228	260	.692
6	150,000		254	279	.667

*This data obtained from transducer location 3.

FIGURE 17

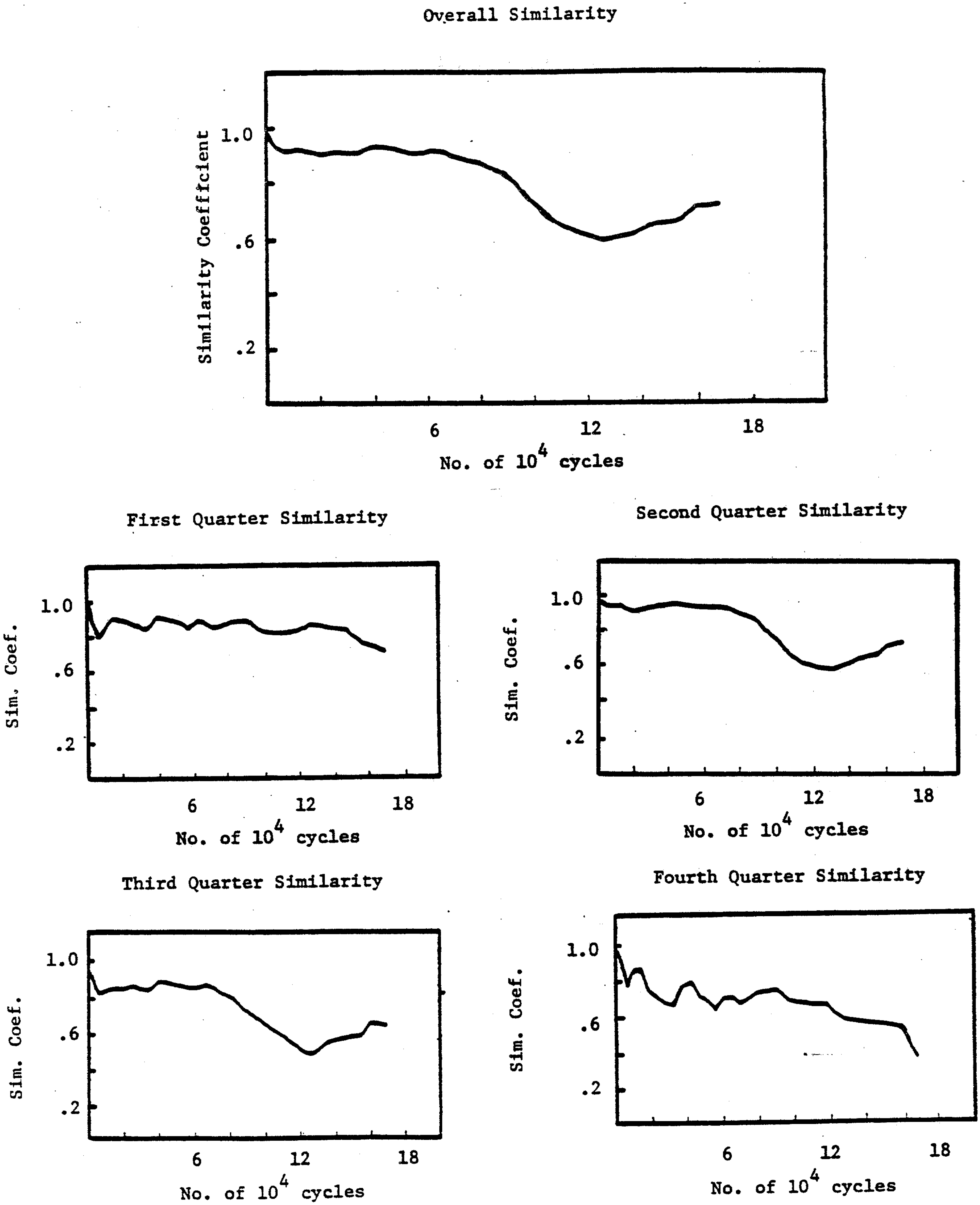
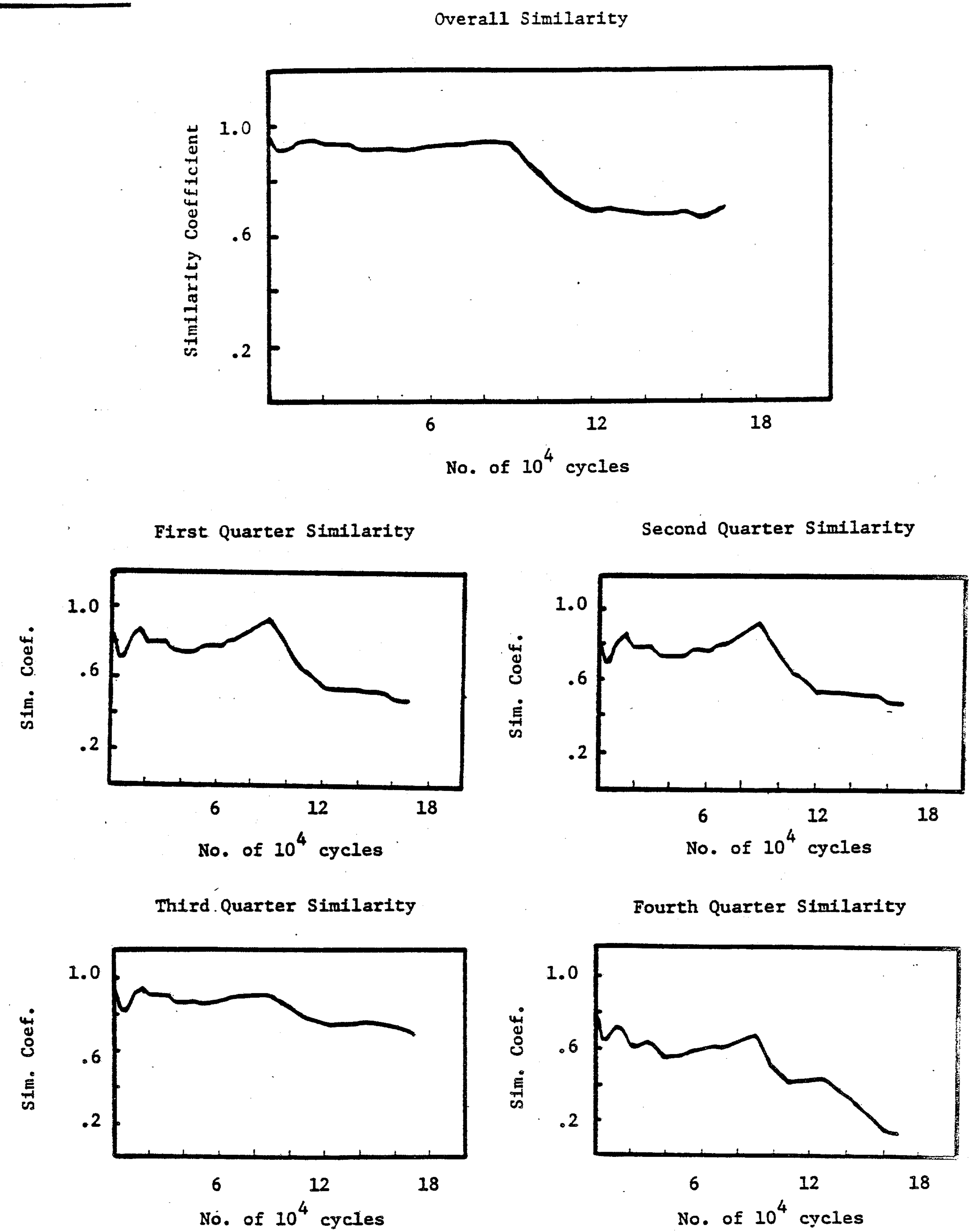


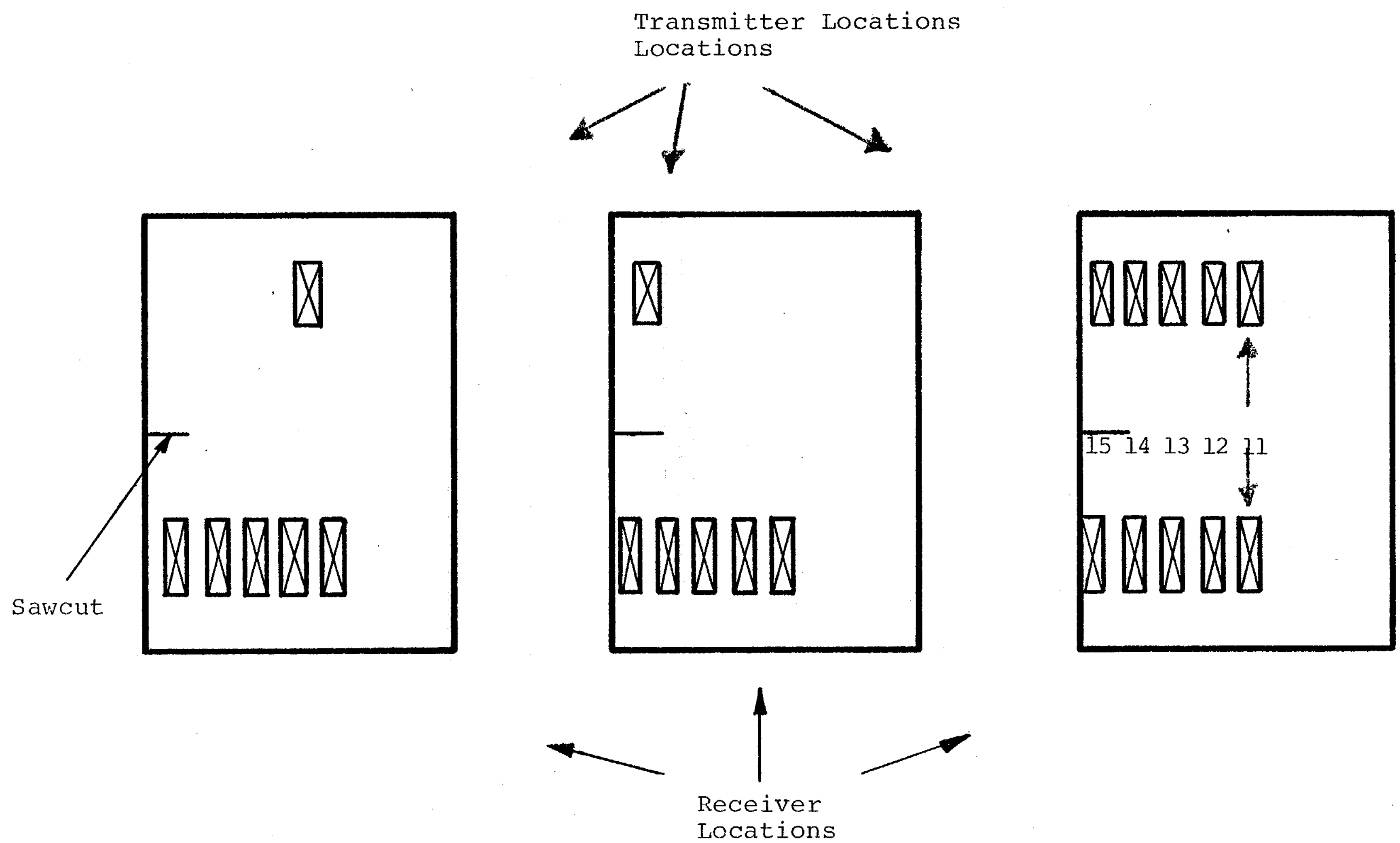
Figure 6—Similarity analysis for data acquisition position 3.

FIGURE 18



Similarity analysis for data acquisition position 4.

FIGURE 19



Transducer placement for evaluation of sensitivity
to perpendicular damage.

FIGURE 20

are interrupting the ultrasonic beam. Here, 15 worked best. 14 worked well. 13, 12, 11 didn't work. So we did a lot of little variations.

We did the barnacle effect with clay. We inserted water, looked at pulse-shape changes, tried to come up with some parameters of value in the technology transfer from the laboratory to a real work application.

We looked at amplitude variations with simulated cracks as well.

In summary, I think we developed a powerful global ultrasonic inspection technique, utilizing lamb wave methodologies which have complete coverage of the joint structure.

We found, by working with the power spectral densities, that they do, indeed, have great sensitivity to damage initiation in the structure. A great deal of work exists in the technology transfer.

We feel that very inexpensively built pulse receivers could be mounted at the transducers, put down in the structure and, by telemetry, get information to the top of the drilling rig on a daily or weekly basis to give us some indication of signal change, hence damage initiation to the structure.

MR. SMITH: On your load spectrum, you said the acoustic method picked it up before the visual crack approved; ultrasound picked it up after the visual crack.

DR. ROSE: Pete, what about that?

MR. ALEA: We picked it up a little bit after Joe's initiation. We picked it up at about 120,000 cycles, when the crack was about 5-1/2 inches long.

DR. LIU: First of all, these transducers are held by hand during the experiments?

DR. ROSE: Yes, for the simulation.

DR. LIU: Were there any contacts between the transducer and the angle?

DR. ROSE: The angle is based on the shoe design itself. That's fixed in the structure. You had mounting guides and so on to ensure they were fitted into the right location.

Now, the coupling variation, of course can change. It would remove the amplitude anyway. So, that's the only thing that would change by pressure.

So, we were sensitive to the coupling variation.

DR. LIU: You're still saying that this is a global technique, global evaluation?

It seems to me it still is local.

Could you make some comment how it would differ, a localized evaluation, where you claim yours to be global?

DR. ROSE: Sure.

In the global technique, first of all, the cracks of that weld could be initiated from four possible points. With this global technique, you wouldn't know which of the four.

In other words, we send energy around the structure. So, there's four possible crack initiation points. With a global inspection technique, we wouldn't know which one it's coming from, because we're interrupting the beam.

Whereas a local inspection, you look at each one, and you know that here's exactly where the crack started.

Also, the sizing of the defect, with the local inspection technique, we'd need to go back and forth to find out how deep the cracks penetrated. With this global technique, we only have an indication -- we can tell the growing increase in cracks, but we don't know the exact functional increase size. That's the difference.

The local can do all those, but the environment is such that it's so difficult to do.

DR. LIU: Are your transducers homemade or are they off-the-shelf items?

DR. ROSE: They're designed by us, and built by KB.

MR. DAVIES: Could I ask you about the frequency transducers? You mentioned going to lower frequencies.

DR. ROSE: 28 megahertz. We also used .3, a third of a megahertz, as well.

MR. DAVIES: So, you're approaching acoustic frequencies.

Have you considered some sort of hybrid possibility, where you might use the same transducers for acoustic emission?

DR. ROSE: That could be a good idea. It might be very good, in fact, because I think the ultrasonic technique at these super-low frequencies would not be as sensitive, so we can go out later on the curve.

DR. GREEN: I wouldn't recommend that, because acoustic emission transmitters, commercially obtained at least, won't be nearly as sensitive.

DR. ROSE: I see.

VOICE: If you fill the K-joint with grout, would that have an effect?

DR. ROSE: No. In other words, we run these tests in the air and some tests in water and also with the barnacles.

It turns out with the .8 megahertz or less, it's not sensitive. If you use higher frequency and want to do this localized ultrasonic inspection, the barnacle, the grout, everything will have an effect.

But with the long wavelength, it more or less doesn't see these variations. It hops right through there.

MR. KNAPP: If you have to place that transducer in a welded-on housing, would that affect your results? Can you calibrate that out?

DR. ROSE: You'd have a hard time separating 20 percent corrosion, through-wall reduction, from a crack, let's say, in this through-transmission mode. We might still develop a procedure. It depends what kind of interest is generated, whether the whole project continues.

MR. WARREN: Is there a chance of monitoring even larger, more complex geometries? Is there a possibility of four K-joint legs with transducers, or are you kind of at the limits?

DR. ROSE: I guess we are really at the limits. In other words, we are in an area 5 inches high, maybe 14 in diameter, wall thickness 1 inch, 2 inches maybe. That is what works well today. Beyond that I am not sure, but I do know the technique can work for any kind of structure.

In fact, we are thinking now of applying this technique to composite areas. If you send energy from one end to the other rather than scanning, feature scan or what have you, looking at the similarity measure of the energy, the dispersal of waves as they run along the composite and move along looking for signal change, a sensitivity study has to be done.

So the whole concept of long wavelength and wave velocity relationships applied to similarity for global inspection. We are going to be trying them on bridges, on composite materials, and all kinds of structures in the future. I know we are going to carry it forward.

Whether the application to offshore structures is carried forward or not, I don't know, but structures in general. It looks very encouraging.

Michael D. Fuller
Drexel University

Acoustic Emission Data Acquired from a 1/3 Scale Model K-Joint Fatigue Test

MR. FULLER: What I want to talk about is a bit of acoustic analysis that was done on the one-third scale model K-joint fatigue test at the same time the ultrasonics was done and at the same time we did the random decrement.

It was a pretty complicated test because we did have three methods going at the same time. Needless to say, we didn't have a lot of opportunity to give acoustic emission a lot of attention during this data acquisition phase. So in that sense it is a valid test of acoustic emission.

(Slide) N.A.

This is the test setup that you have seen, I guess, twice before, but I would like to point out a couple of different things. You can see, whoever it is who asked the question about placing the ultrasonic transducers, if you will notice this line here, these are 90-degree jogs, where each transducer location was placed.

There is another set of jogs on the other side. But as far as acoustic emission is concerned we had four transducers. These transducers were resonant sensors of about 150 kilohertz. Their signals go through preamplifiers.

This particular preamplifier doesn't have any connection coming out of it. We were trying the new probe here which has the preamplifier already in it. These are commercial transducers from Physical Acoustics Corporation.

We mounted all this equipment on here, excited the thing for approximately two weeks, 2000 minutes of actual run time, approximately 190,000 cycles.

(Slide) N.A.

This is the failure that we got. Now we showed a slide similar to this yesterday, and you saw this crack. It is about a three-inch gap down here, and the leg almost fell off.

So it was quite a catastrophic failure. Like I said, we had 2000 minutes of actual acoustic emission data, which is 23 floppy discs. So there is a lot of information to analyze.

It took us a lot of time, but we did get some interesting results. I think it is valuable to the community, and I would like to share it with you.

This is Figure 1. The things we drew from all that data are amplitude behavior, which seems to correlate well with what you would expect, no real surprises.

Event rate behavior seems to correlate well with what has been done in the past by previous researchers. Some concern has been expressed in the past about acoustic emission's sensitivity to platform noises and uncontrolled noises that the operator can't do anything about. We had some of that in there.

We had Pete Alea's shaker and our ultrasonic transducers pulsing into the acoustic emission. We could tell when it was on. I will show you some of that.

Finally, signal character. We were able to look at the data in a couple of different fashions which suggest that some advanced work in signal character could help us to discriminate between acoustic emissions from cracks or whatever flaw that you are interested in, which is promising.

This is Figure 2. In the way of amplitude behavior, I would like to start off, of course, from the beginning of the fatigue test, 0 to 3000 cycles.

What we have here on the Y axis is the number of total events occuring in this time period, and on the X axis is the total amplitude of the signal, ranging from 0 to 100db. You will notice our average amplitude here is about 52 db. This takes place when there is no damage in the structure whatsoever.

Figure 3 shows that the next record was taken -- of course similar type behavior, but this time 61 db amplitude.

Figure 4 is 61 db.

Figure 5 shows a tremendous increase in the amplitude of the signals. Some of the events are occurring at almost 90 db, and there are 5000 total events in this particular record.

This particular record took about six hours to accumulate. But if there were only one of these, you might think it is a fluke or some external mechanism.

AMPLITUDE BEHAVIOR

RATE BEHAVIOR

CONSIDERATION OF EXTERNAL NOISE

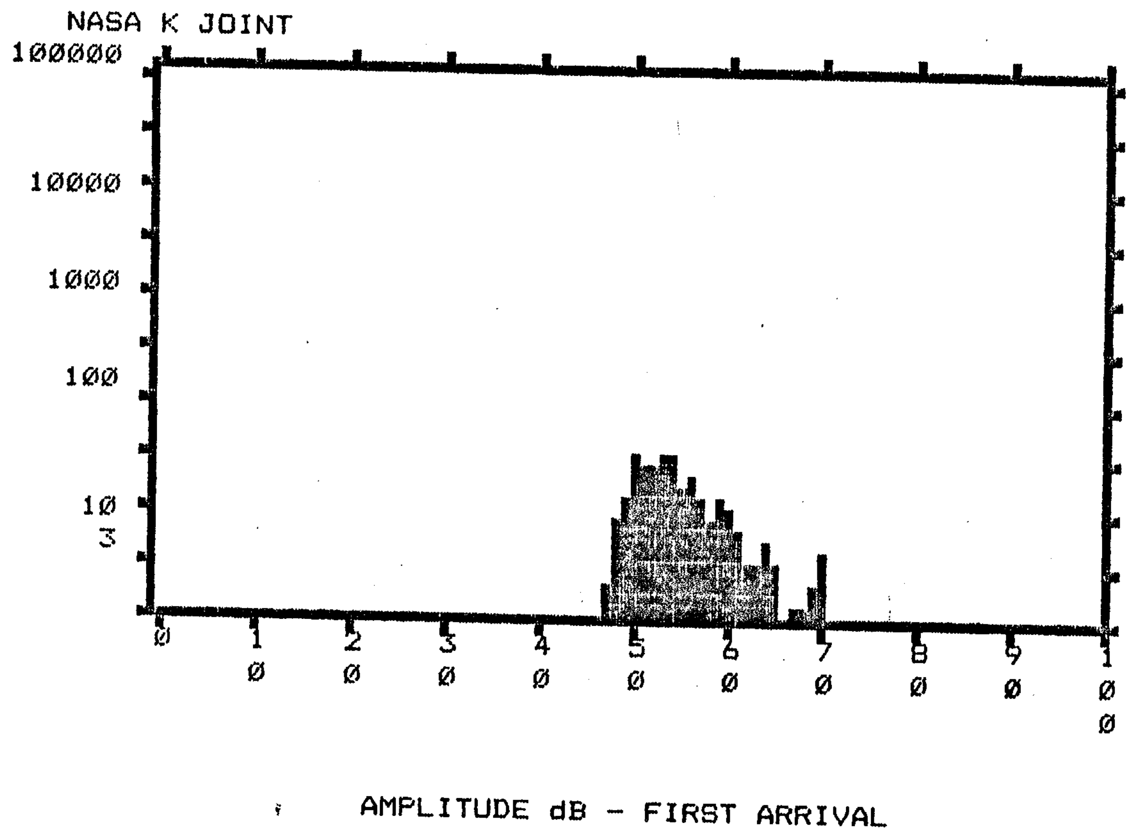
SIGNAL CHARACTER

FIGURE 1

EVENTS

FIRST ARRIVAL

TOTAL EVENTS = 294



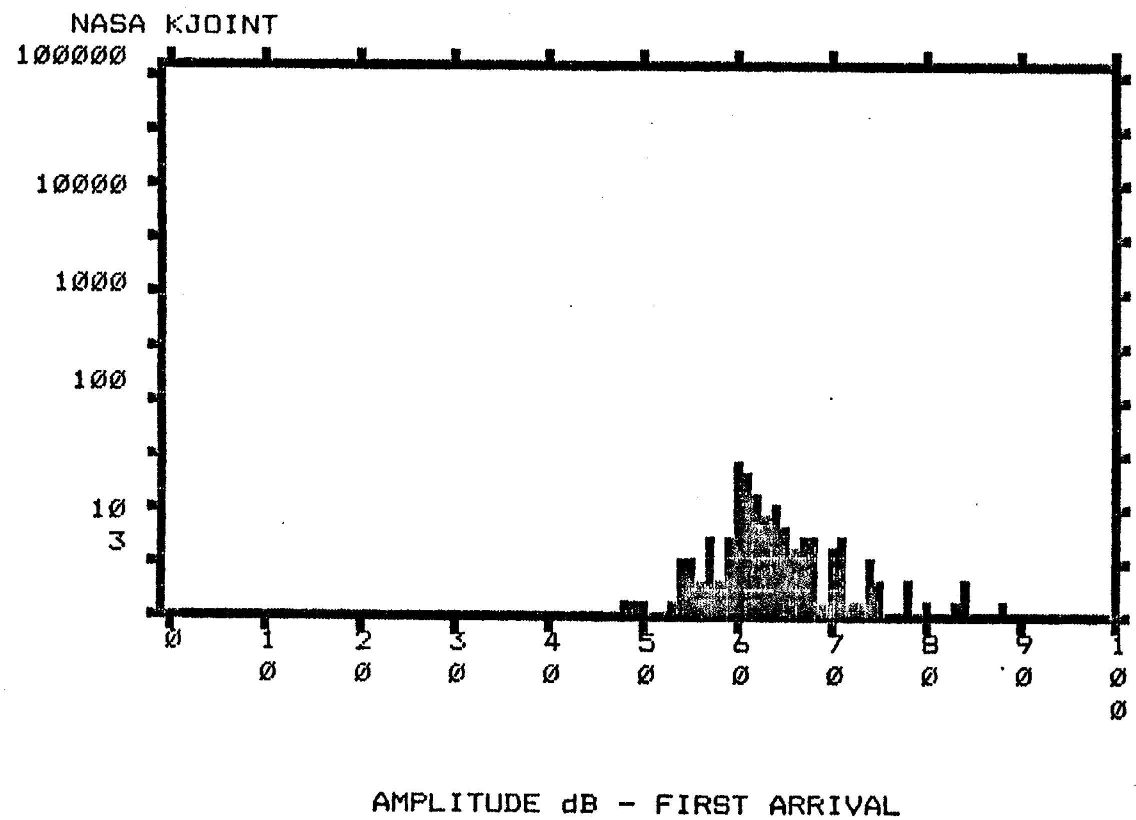
(O-3) KC

FIGURE 2

EVENTS

FIRST ARRIVAL

TOTAL EVENTS = 151



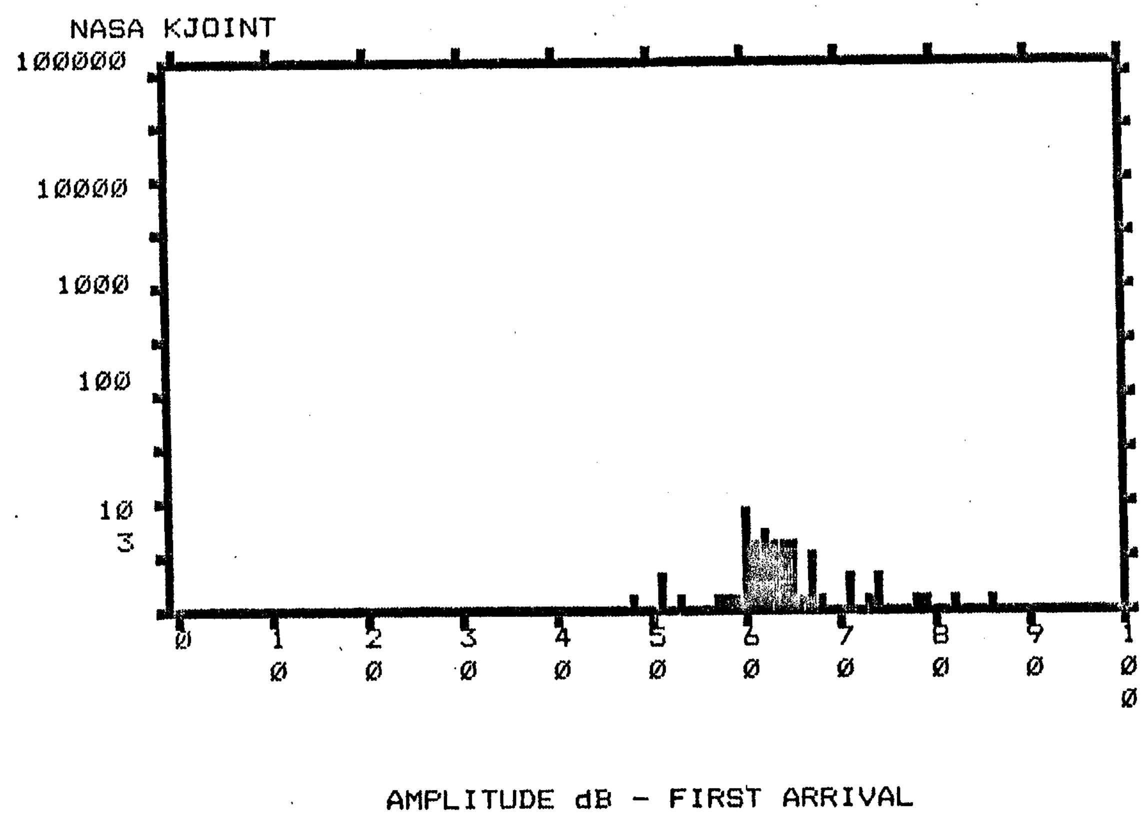
(3-5) kC

FIGURE 3

EVENTS

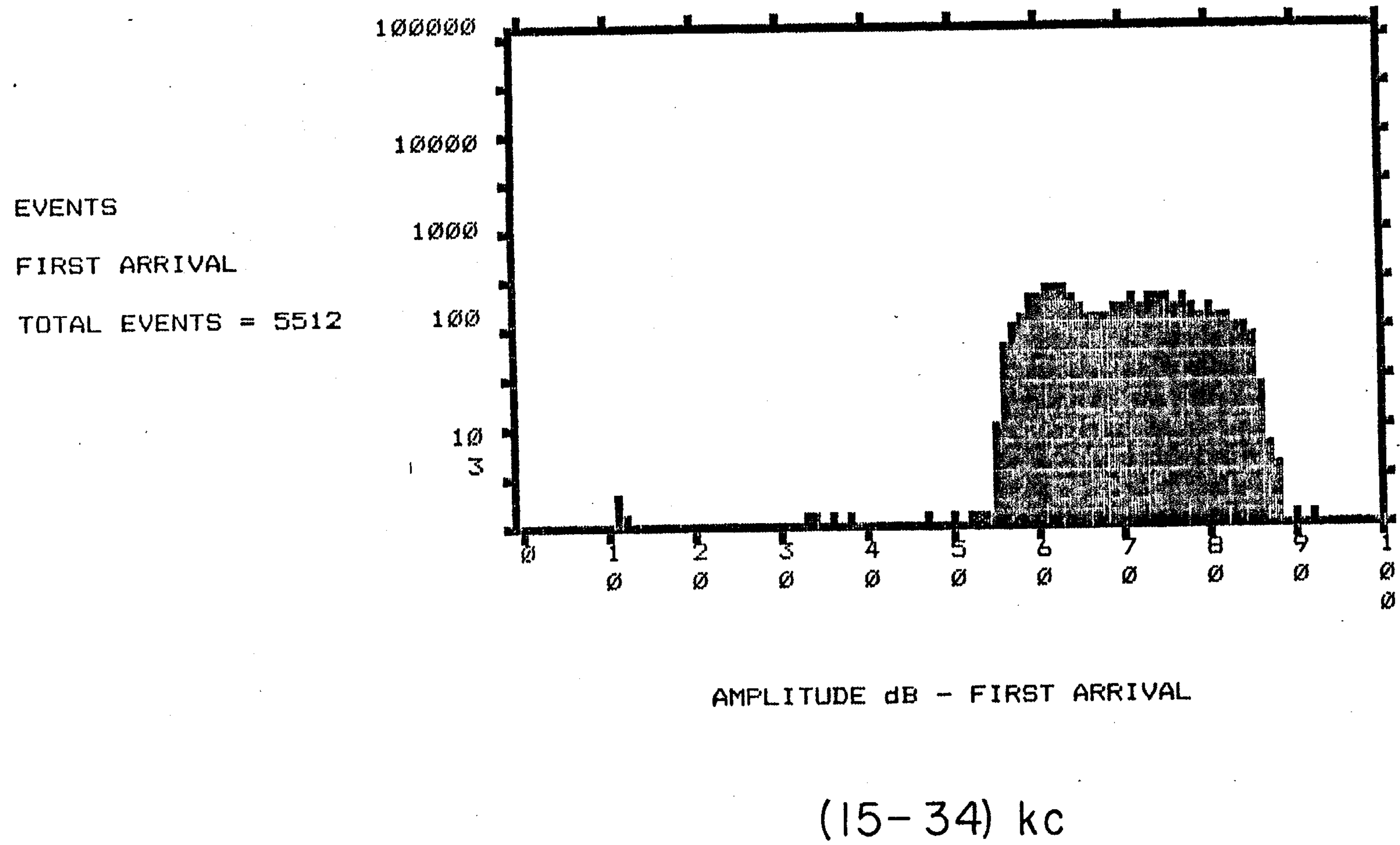
FIRST ARRIVAL

TOTAL EVENTS = 51



(8-10) kc

FIGURE 4



EVENTS
FIRST ARRIVAL
TOTAL EVENTS = 5512
100000
10000
1000
100
10
3
0
10
20
30
40
50
60
70
80
90
100
AMPLITUDE dB - FIRST ARRIVAL
(15-34) kc

FIGURE 5

Figure 6 shows that that kind of activity continued to 57,000 cycles.

This is Figure 7. 79,000 cycles, still very high amplitude activity, at which point, 79,000 cycles --

(Slide) N.A.

-- we noticed these cracks which Dr. Rose showed you earlier. •

Now, about the depth of the cracks. We could tell how deep the crack was because as the ram was cycling -- it was very easy to see the depth. When the legs were spread apart, you could see almost anything you wanted in there. The flexure of the legs was on the order of 5 to 6 inches, so there is a lot of movement.

But at this point, these were surface type cracks. In fact, they weren't visible to the naked eye. The reason that we found them is that we were very, very frustrated that we weren't getting cracks. So we went around with Q-tips and everything we could find to help us get a handle on when the thing was going to start to crack.

Again, this right crack is about 5 inches long. The left crack is about 4 inches long. From this point on, the crack propagates at a fairly rapid rate -- rapid rate about an inch an hour at 2 hertz.

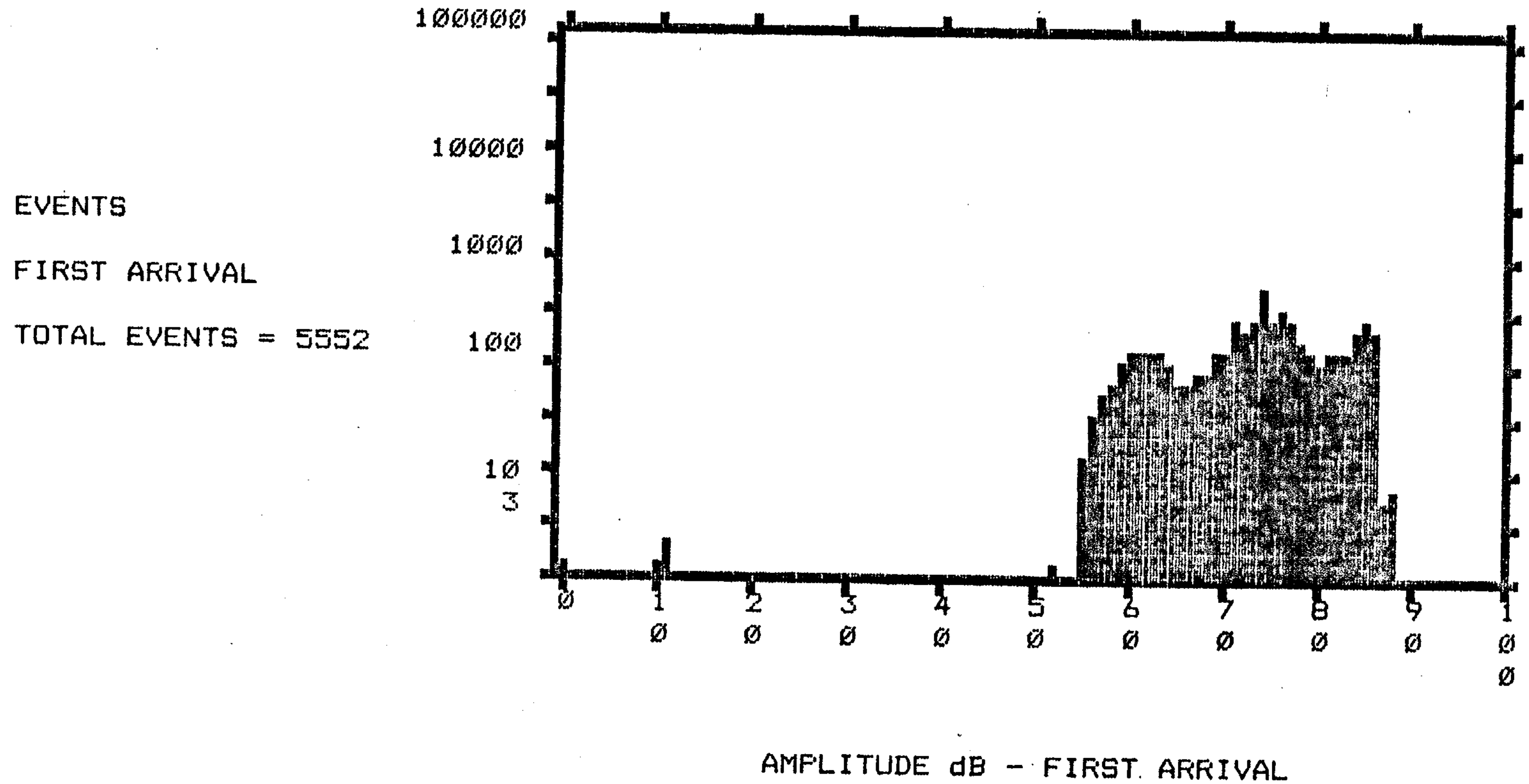
Figure 8 shows the continuation of the high amplitude activity;

Figure 9 (N.A.) until about 150,000 cycles.

At this point the crack changes direction. It arrests itself. It failed to grow any further.

This is Figure 10. And the acoustic emission behavior, you see the decrease in amplitude back down to about 60 db. So this is the amplitude behavior, we know the crack propagation formation at least from this data. We tended to draw the conclusion that when the crack originates and propagates, the amplitude of the acoustic emission goes up.

Of course, there is some subjectivity in where one sets the amplitude threshold.



(38-57) kc

FIGURE 6

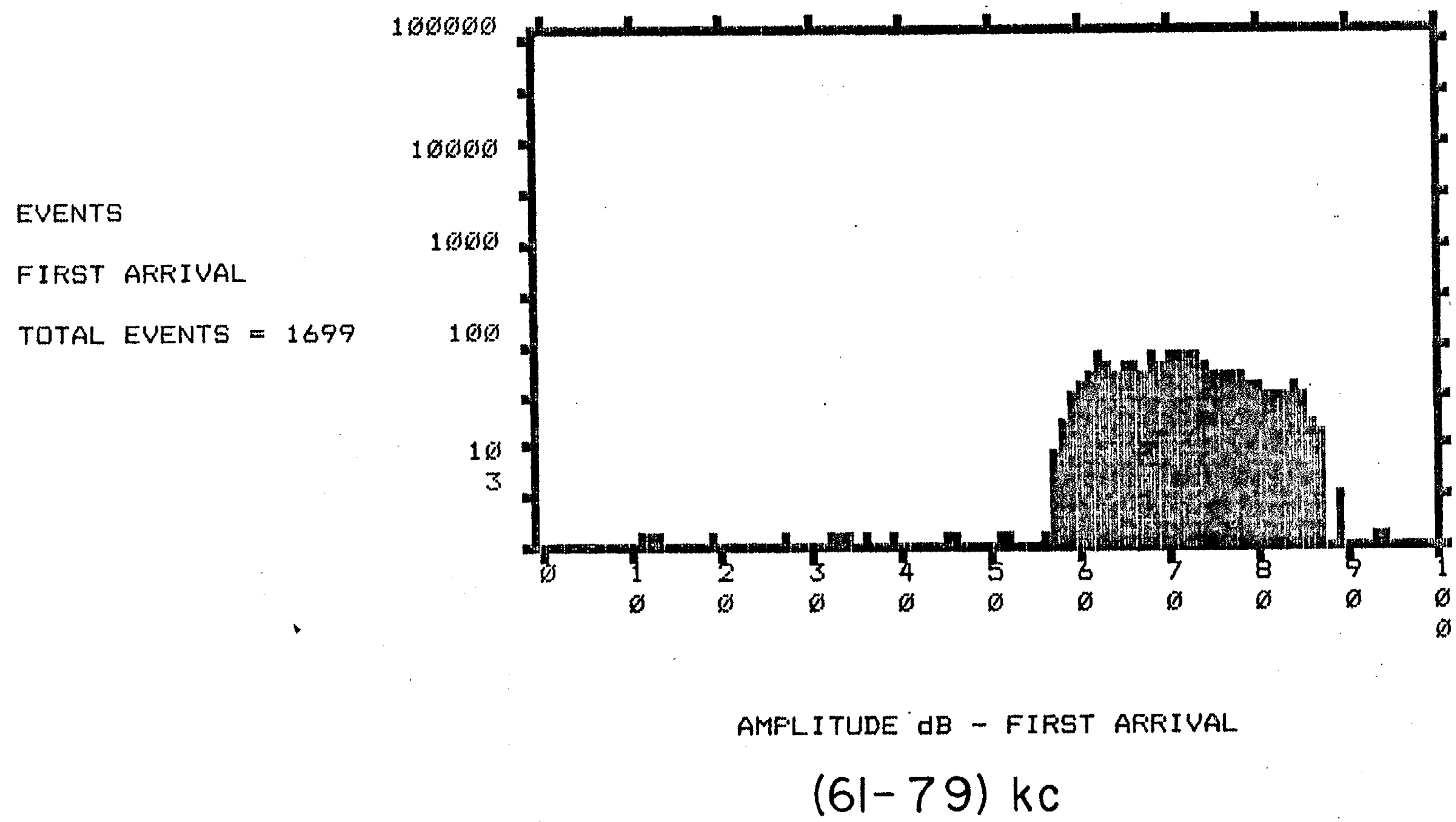
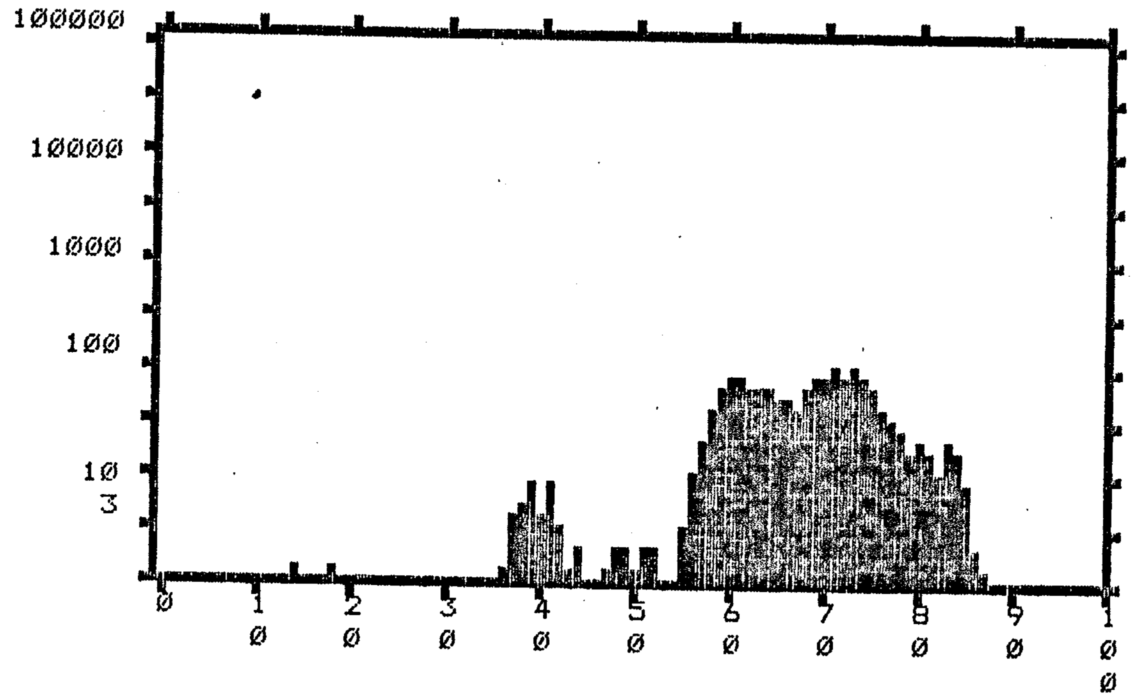

EVENTS
FIRST ARRIVAL
TOTAL EVENTS = 1699
100000
10000
1000
100
10
3
0
10
20
30
40
50
60
70
80
90
100
AMPLITUDE dB - FIRST ARRIVAL
(61-79) kc

FIGURE 7

EVENTS

FIRST ARRIVAL

TOTAL EVENTS = 5517



AMPLITUDE dB - FIRST ARRIVAL

(79-107) kc

FIGURE 8

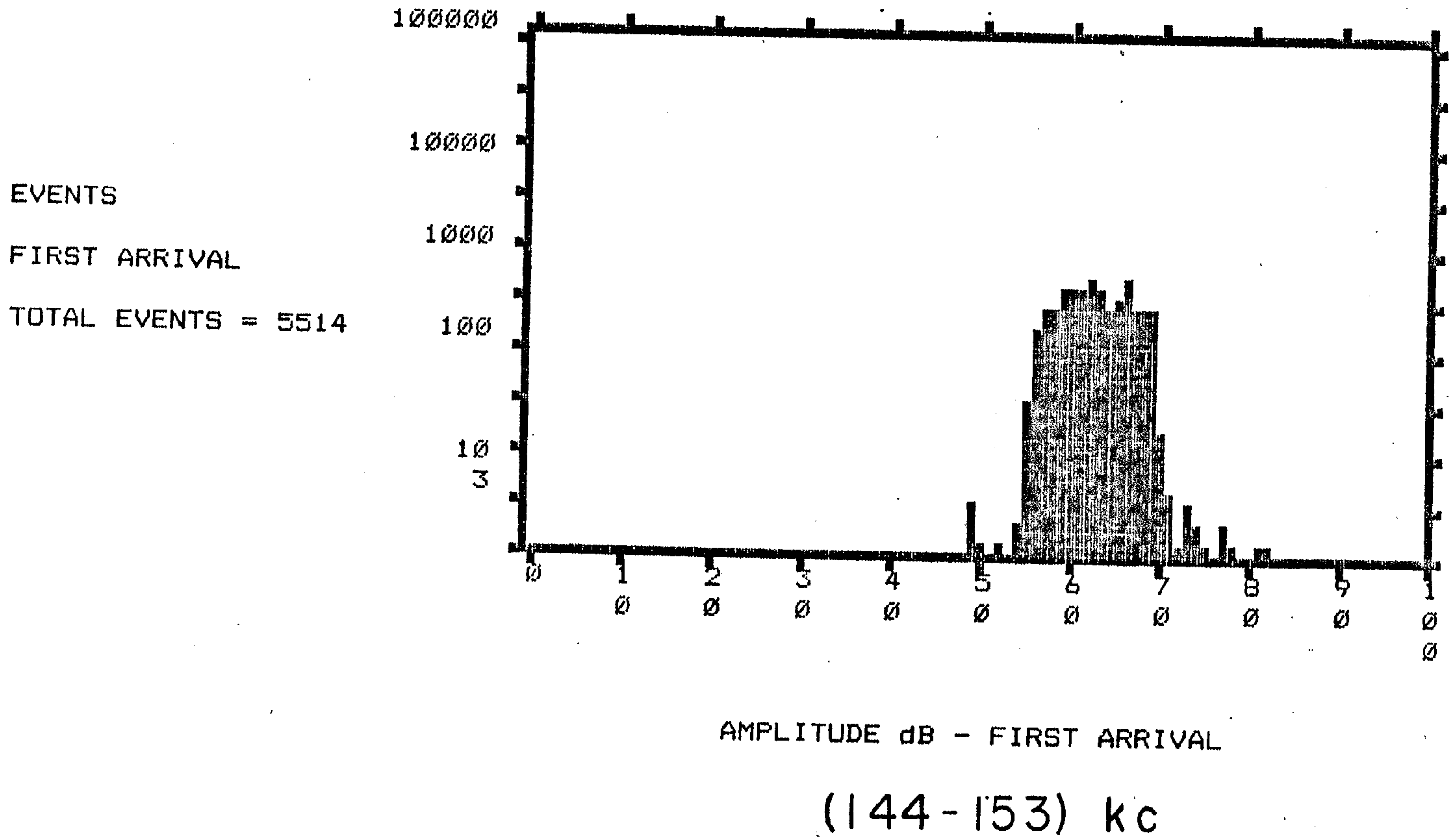

EVENTS
FIRST ARRIVAL
TOTAL EVENTS = 5514
100000
10000
1000
100
10
3
0
10
20
30
40
50
60
70
80
90
100
AMPLITUDE dB - FIRST ARRIVAL
(144-153) kc

FIGURE 10

If I had set it up here at a 100, I would have still assumed that there is a perfect structure in place.

Fortunately, we did have some very good help in setting thresholds. So we got good results.

This is Figure 11. Now I would like to talk about the acoustic emission rate. What I have here is a slide from previous researchers' work, very complicated. There are a lot of things on here.

But if I can draw your attention to this dashed line, this represents the acoustic emission rate over a fairly long fatigue test. What we see is that the acoustic emission rate starts out low, comes up and down. It is very, very jagged. In fact, at failure the acoustic emission rate is still very low. So the acoustic emission rate may not be a good indicator of failure.

Figure 12 shows a six-hour portion of the record showing variations in the event rate. When you start the test cycling, there is nothing. Then we get an event rate of 290 events per minute; goes down to nothing; then you go up to a tremendous event rate of 2590 per minutes for a few minutes. It comes down, nothing. Then again a high event rate for the rest of the day.

So we believe it is consistent with what has been observed in the past by other researchers.

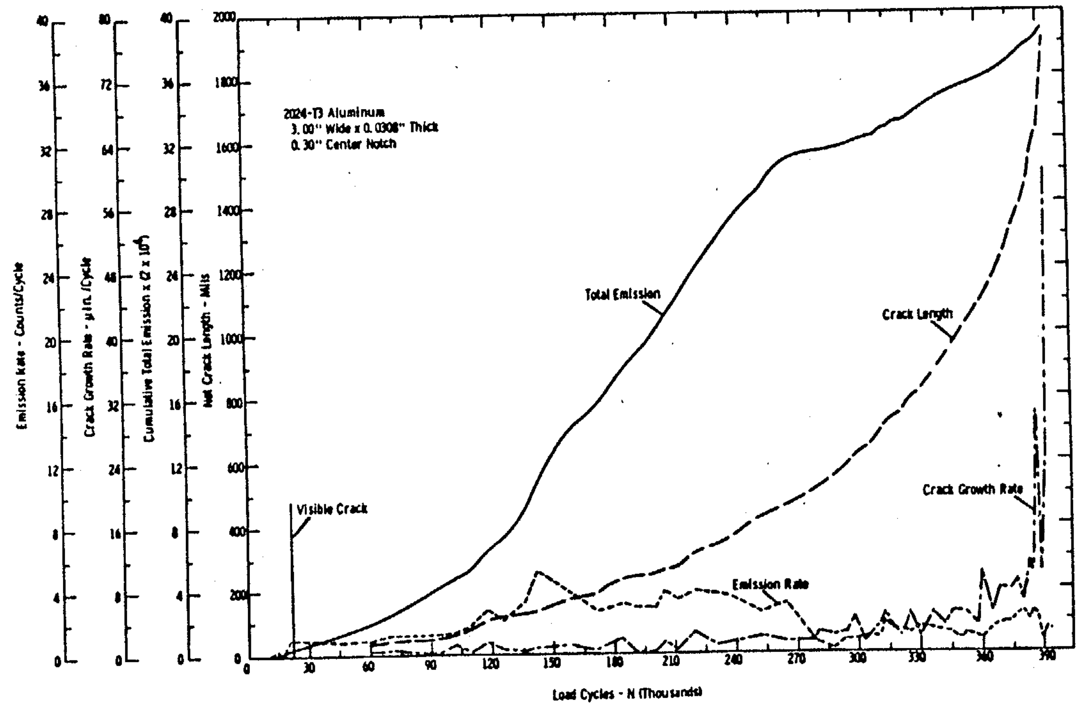
Figure 13 shows that the point of this is that a K-joint is a complicated geometry, yes, but maybe not so complicated it is going to give us something that we don't expect.

What I have displayed on this table is the average event rate per disc, which could be misleading because of the variation in the events through the disc. But it does give you a good indication that we started out low during the crack propagation phase. We had very high events, 500 events per minute, during our crack formation phase.

In this area where we have low event rates, cracks actually propagated macroscopically, when we could measure it. Very low event rates.

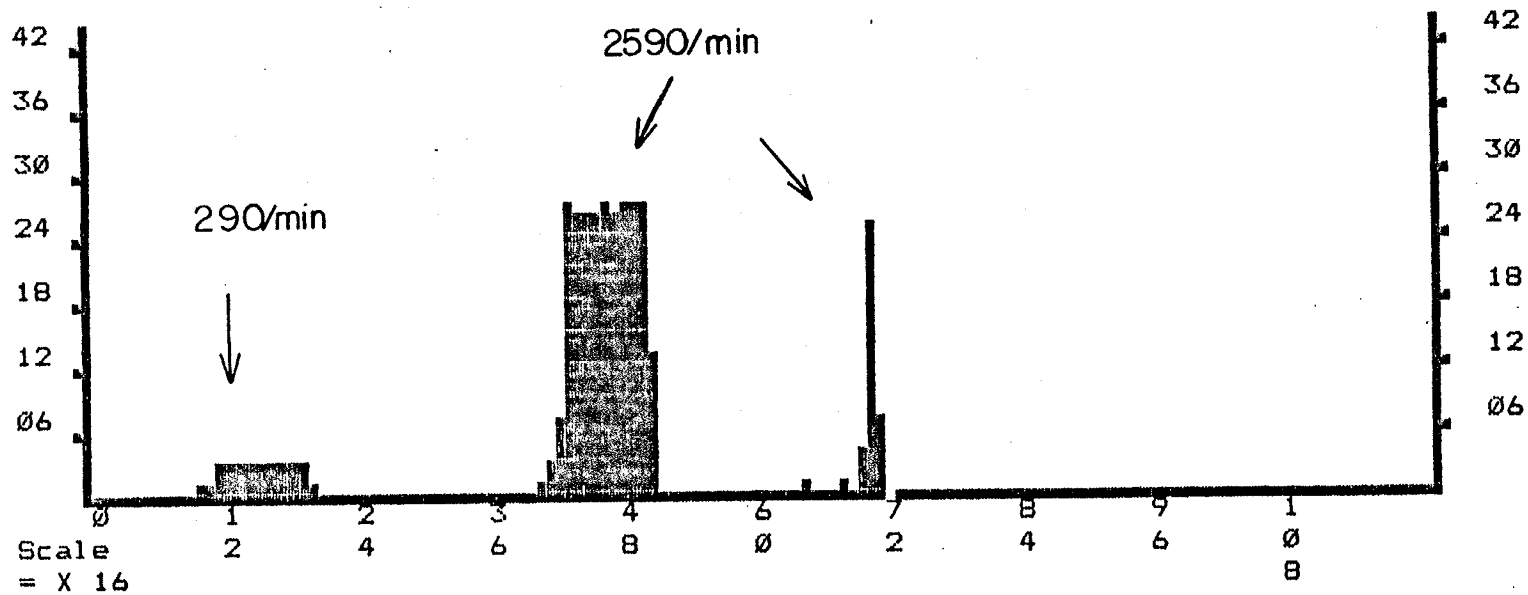
And after crack growth cessation, the event rate goes back up.

Again, I want to emphasize that these are average values. To get true event rate pictures, you would have to go into



Taken From Acoustic Emission Techniques and Applications By J Spanner

FIGURE 11



Time per Tick [X 100 ms.] : 0100

MODE: Replay of Events vs. Time

FIGURE 12

A.E. Event Rate for K-joint

Disk No.	Average Event Rate (Evt/min)	Time (min)	Elapsed Time (min)
1R	15	0 - 19	19
2R	202	19 - 46	27
3R	497	46 - 57	11
4R	500	57 - 196	139
5R	390	196 - 210	14
6R	455	210 - 222	12
7R	30	222 - 257	35
8R	15	257 - 602	345
12R	12	642 - 1092	450
15R*	4	1122 - 1552	430
16R		1552 - 1956	404
2B	390	1980 - 1994	14
3B	515	1994 - 2000	6
8B	73	2380 - 2454	74
9B	160	2454 - 2488	34
10B	455	2488 - 2500	12

*Cracks Detected with Dye Penetrant

FIGURE 13

the event versus time display for that particular record and get exact values, but it is an indicator.

This is where we noticed that the cracks existed.

One other thing that I might note, right in here there is a lot of missing data. We had an equipment problem, and that data is not reliable.

Figure 14 shows the data associated with 15- to 34,000 cycles a little bit more in detail as far as foreign events are concerned, ultrasonic contamination. This is the amplitude picture for reference.

Figure 15 shows that what we have displayed on this plot is the number of events on the Y axis. On this scale you multiply everything by 32. Time is on the X axis.

Let me tell you the test protocol a little bit. The test protocal called for turning on the ram and cycling the structure for 45 minutes. At the end of 45 minutes, NASA acquired random decrement data by turning on their 7 pound shaker, running for two minutes, then turning off the ram and running for another two minutes with the shaker. Then we would acquire our ultrasonic data. Then in 45 minutes a repeat of the same thing.

What we see here is that this block is 45 minutes long. This block is approximately two minutes long. It is the shaker data.

It may be difficult to say this is actually shaker data, but an interesting point is that we have shaker data when the ram is cycling. We have no shaker data when the ram is not cycling.

So what happens is while the ram is cycling and the shaker is turned on, thereis an acoustic emission being generated. When the shaker is on by itself, no emission is being generated.

This behavior, by the way, of the shaker was not noted. There was no acoustic emission at all, cycling or not cycling. It could be a vital damage detection mechanism.

Figure 16 looks similar to the previous plot, but in actuality it is not. It is amplitude on the Y axis versus time.

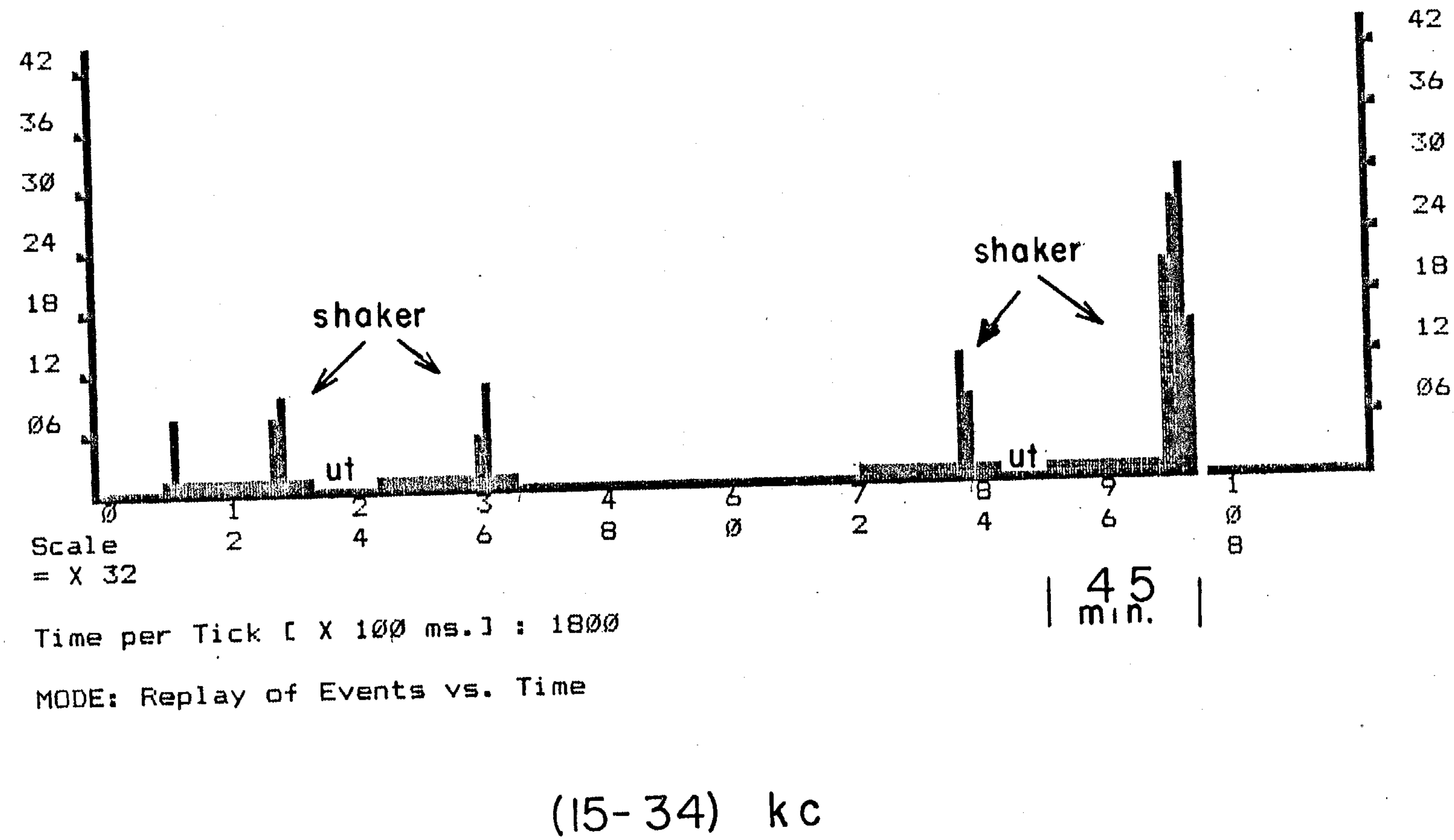
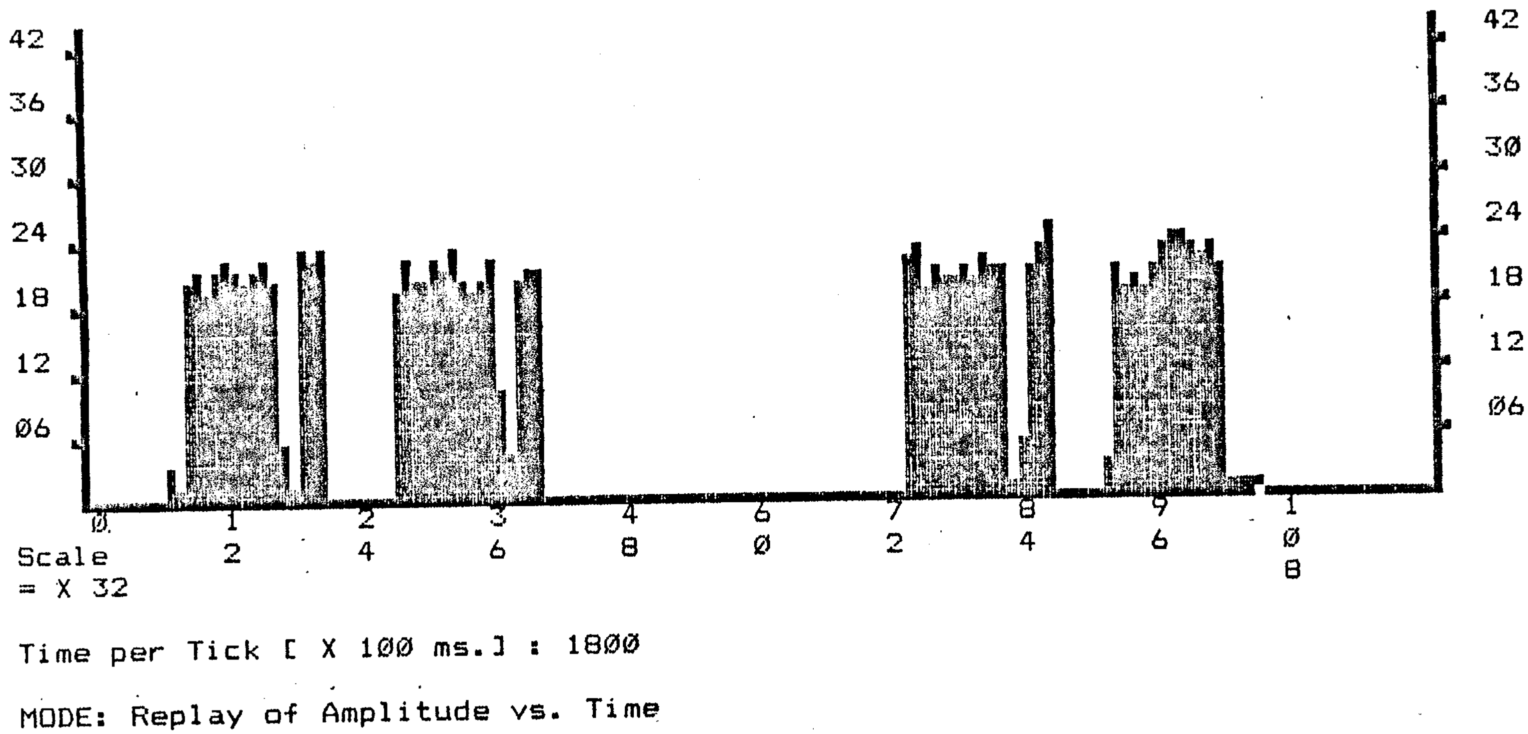
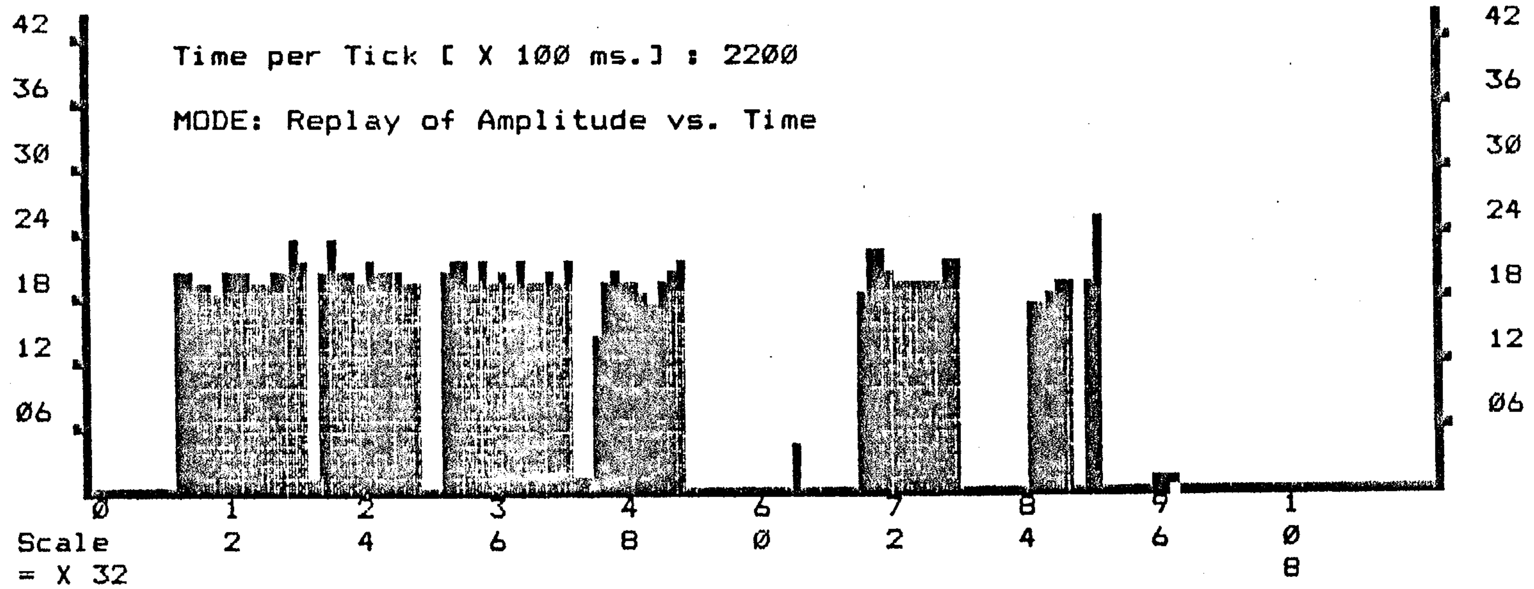

42
36
30
24
18
12
06
shaker
ut
shaker
ut
0
12
24
36
48
60
72
84
96
108
Scale
= X 32
45 min.
Time per Tick [X 100 ms.] : 1800
MODE: Replay of Events vs. Time
(15-34) kc

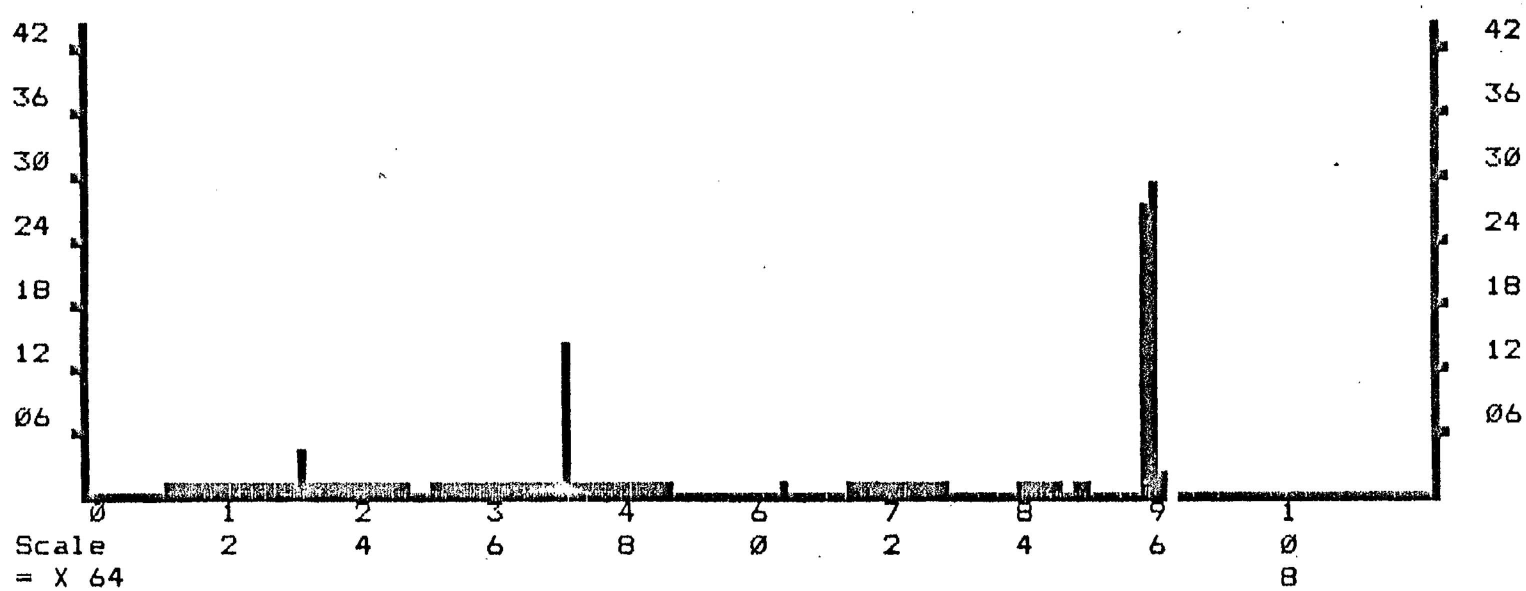
FIGURE 14



(15-34) kc

FIGURE 15





Time per Tick [X 100 ms.] : 2200

MODE: Replay of Events vs. Time

(69-107) kc

I would like to correlate this very, very low amplitude portion here, this very low amplitude portion here, this very low amplitude portion, and this very low amplitude portion here. They correlate time-to-shaker data.

We noticed actually when the shaker came on -- NASA kept excellent notes, to the second when they turned the shaker on and when they turned it off -- and we used the clock that was used on the acoustic emission equipment. So everything correlates well.

So shaker data is low amplitude data. It doesn't really affect our crack detection as far as the amplitude data.

I would like to look at this one in a bit more detail again. This is high amplitude data. The crack has been propagated at 79,000 cycles.

This is just to show that the shaker data is consistent -- shaker, shaker, shaker. The reason it doesn't appear at the end is because you increase your run time to get your cycles in. So the thing finally breaks.

These blocks are an hour and a half long. But the shaker is put on at the end of 45 minutes. So we will still have the shaker data. The low amplitude does correlate to these spikes.

VOICE: Do you have an explanation for why that is so low?

MR.FULLER: It is only a 7-pound shaker, and any noise that would be generated from, say, the crack vibrating has got to be much lower than the strain energy for crack propagation.

That is my initial theory. I would like to look at it further.

DR. GREEN: What is the vibrational frequency of the shaker, and what is the vibrational frequency of the ram?

MR. ALEA: The vibrational frequency of the shaker is roughly 22 kilohertz. The ram is cycled at 1.6 hertz.

MR. FULLER: The ram variation -- it varied a little bit in that the crack grew. So the maximum rate we could keep the ram at was what we kept it at.

DR. GREEN: You have got acoustic emission on both of them?

MR. FULLER: That is right. So we believe we can detect a small amplitude contamination such as a shaker if we know when it is turned off.

Figure 17 is an example of further contamination. This is when we forgot to turn the acoustic emission pause button. I[t] contaminated the data very well. As a matter of fact, the event rate is very, very high. It caused us to waste quite a few.

In between those 45-minute intervals we see those very high spikes.

This is Figure 18. I would like to look at some interesting plots which I don't have really any conclusions on as yet. We had the capability with the software provided to look at correlation type plots.

What we have on the X axis here is pulse duration or event duration in microseconds, and we have a number of counts that occur in that event on the Y axis.

What I have here in 3- to 5 kilohertz is what I consider a good K-joint, one with no cracks. We look at the events, and we see behavior that is grouped in this area here.

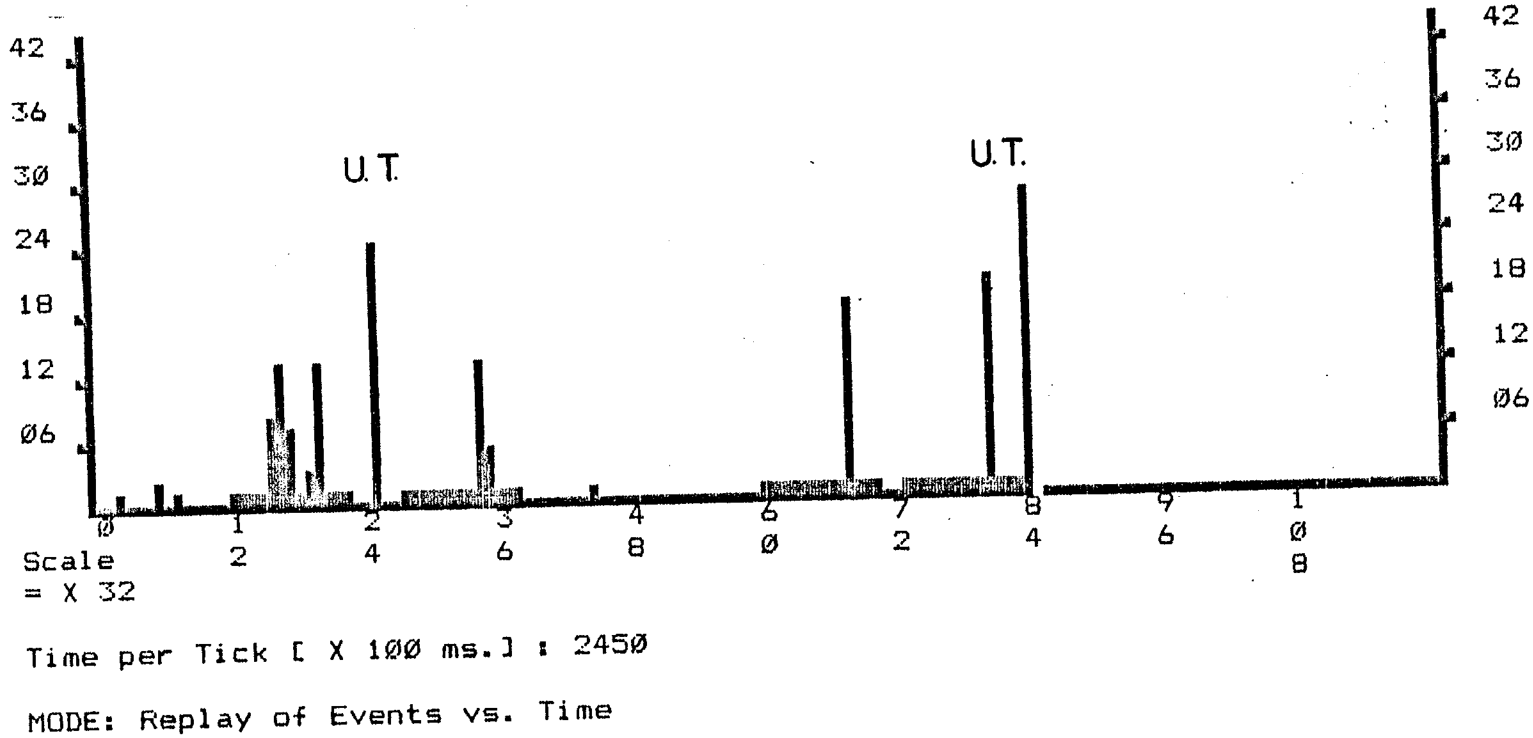
There are 5000 events here. So a majority of the events, say 3000 of them, are in this area down here.

Figure 19 shows that what we did was look at an area where 60 to 100 db events, between 61- and 79,000 cycles. We know that this is an area where there is cracking definitely.

In official measurements we see the population seems to spread out in a uniform fashion, linear fashion.

Figure 20 shows that what is displayed here is a record where we had a bimodal distribution of amplitude. You see this linear behavior, and we also see a large concentration here, along with some concentration here.

It was very curious to us. We wanted to know exactly what happened. This is crack mechanism, and this is a frictional mechanism here, in which event this particular plot is a good indicator of frequency. If you take the pulse time here and the number of counts, you can get some indication of frequency.



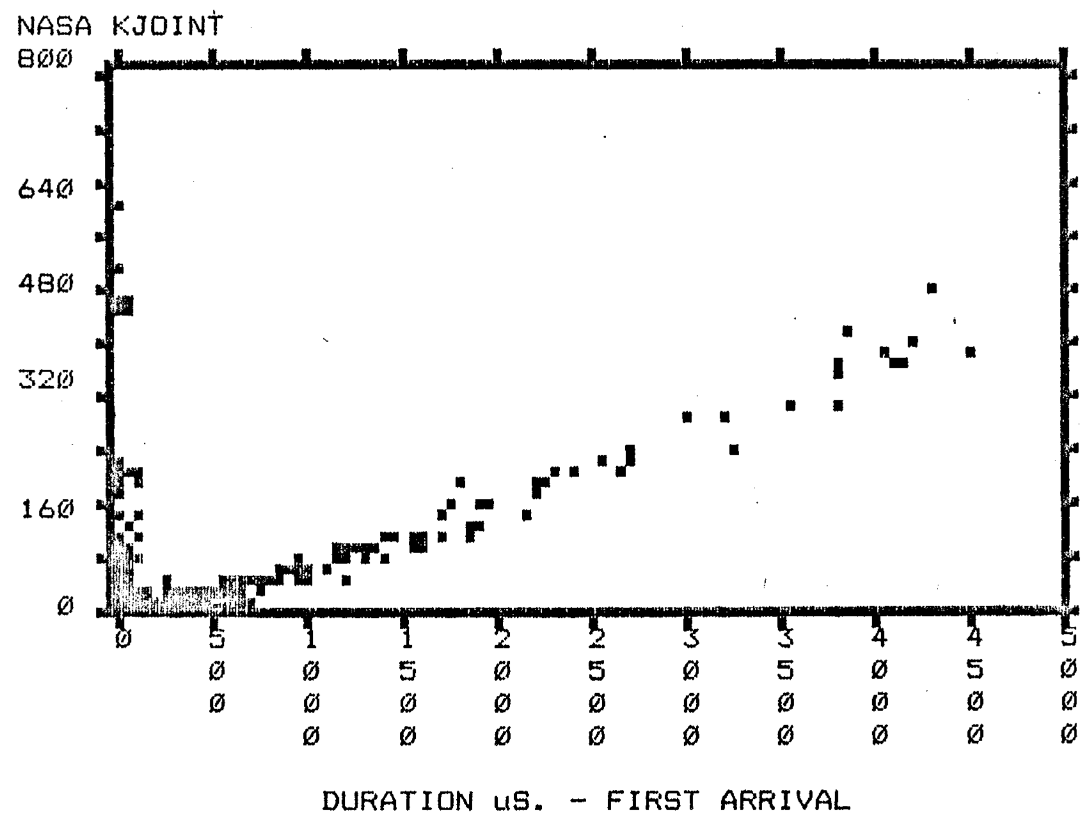
(38-57) kc

FIGURE 17

COUNTS

FIRST ARRIVAL

TOTAL EVENTS = 5515



(3-5) kc   55-65 db events

FIGURE 18

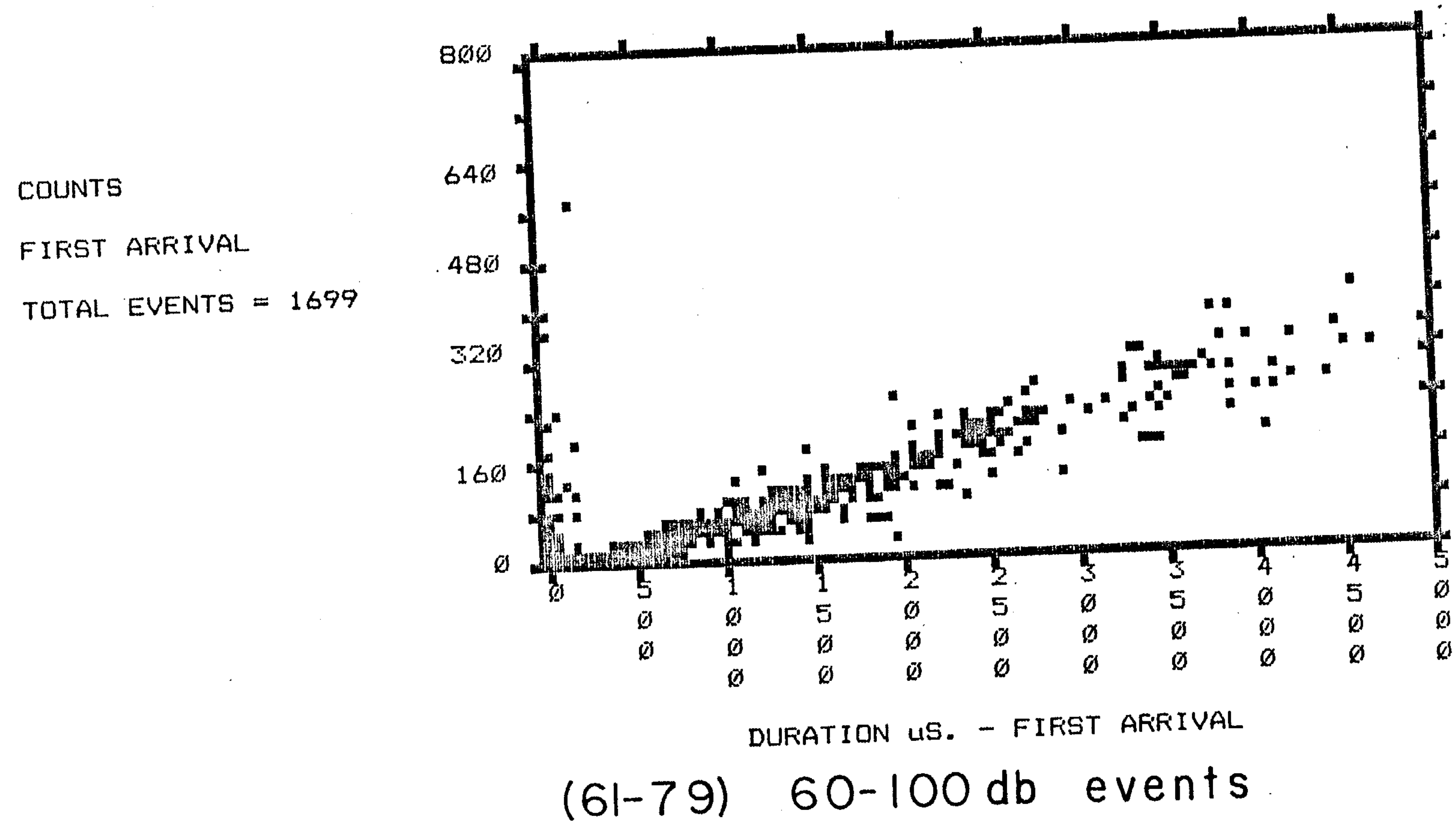

COUNTS
FIRST ARRIVAL
TOTAL EVENTS = 1699
800
640
480
320
160
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
DURATION uS. - FIRST ARRIVAL
(61-79) 60-100 db events

FIGURE 19

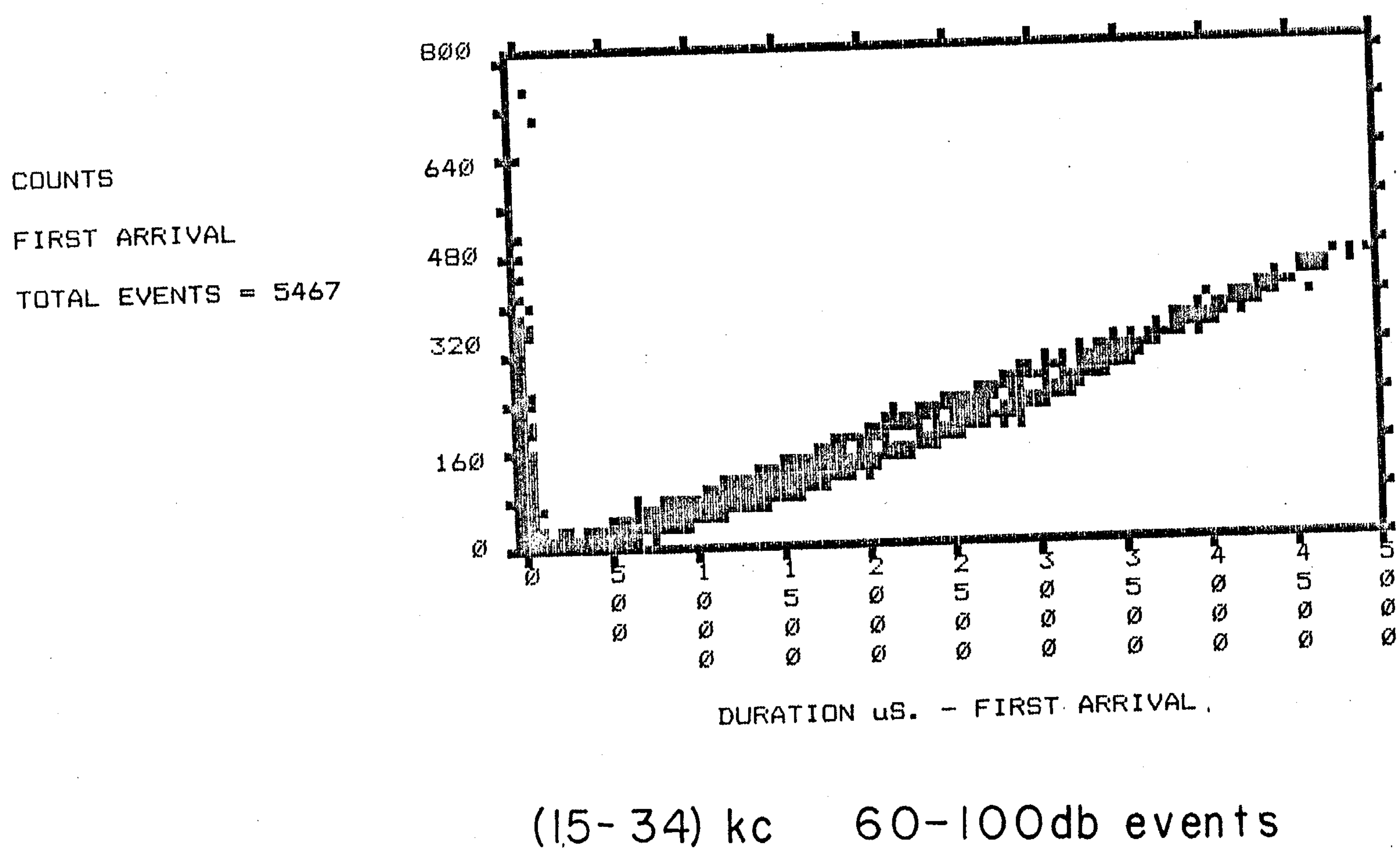

COUNTS
FIRST ARRIVAL
TOTAL EVENTS = 5467
800
640
480
320
160
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
DURATION uS. - FIRST ARRIVAL.
(15-34) kc 60-100db events

FIGURE 20

So we took that record 15 to 34 kc, and we only looked at the first hump of the bimodal distribution between 55 and 65 db.

Figure 21 shows that what we got, the concentrations down here.

So on that I would like to postulate that it may be possible to look at acoustic emission events and do this type of analysis or some further frequency analysis and maybe characterize those events, which may be helpful in determining exactly what it is that seems to be a problem.

Again, if you set your threshold down here, you will miss everything, but you can tell by looking at the event, not what its amplitude, but what it is, it is going to be very useful.

Figure 22 shows that after a lot of work with 130,000 events, we came up with some fairly decent conclusions.

One is that the K-joint is an excellent emitter of acoustic emissions, and it is very feasible to try this technique on a K-joint. It is a good emitter. You get a lot of events. The amplitude behavior correlates well with what we expect. No real surprises.

The geometry really doesn't throw us off that much. The rate data correlates well with what previous researchers have done. There's not surprises there. And we are confident in the technique there.

It is possible to acquire data from this very complex geometry, using commercially available equipment, which is good equipment that has a lot of software with it.

From underwater -- I had a probe here; that is always something you forget. It has got a preamplifier in it. So we acquired data from 1000 feet -- no effects.

This is Figure 23. So I'd like to make some recommendations.

The first one is, frequency analysis and signal classification can be done a lot better today than in the past. The equipment we had was not adequate for doing that analysis. Digital computers can be very useful, I think a lot of you would agree. A study of the shaker generated acoustic emissions for damage detection mechanism, it's an

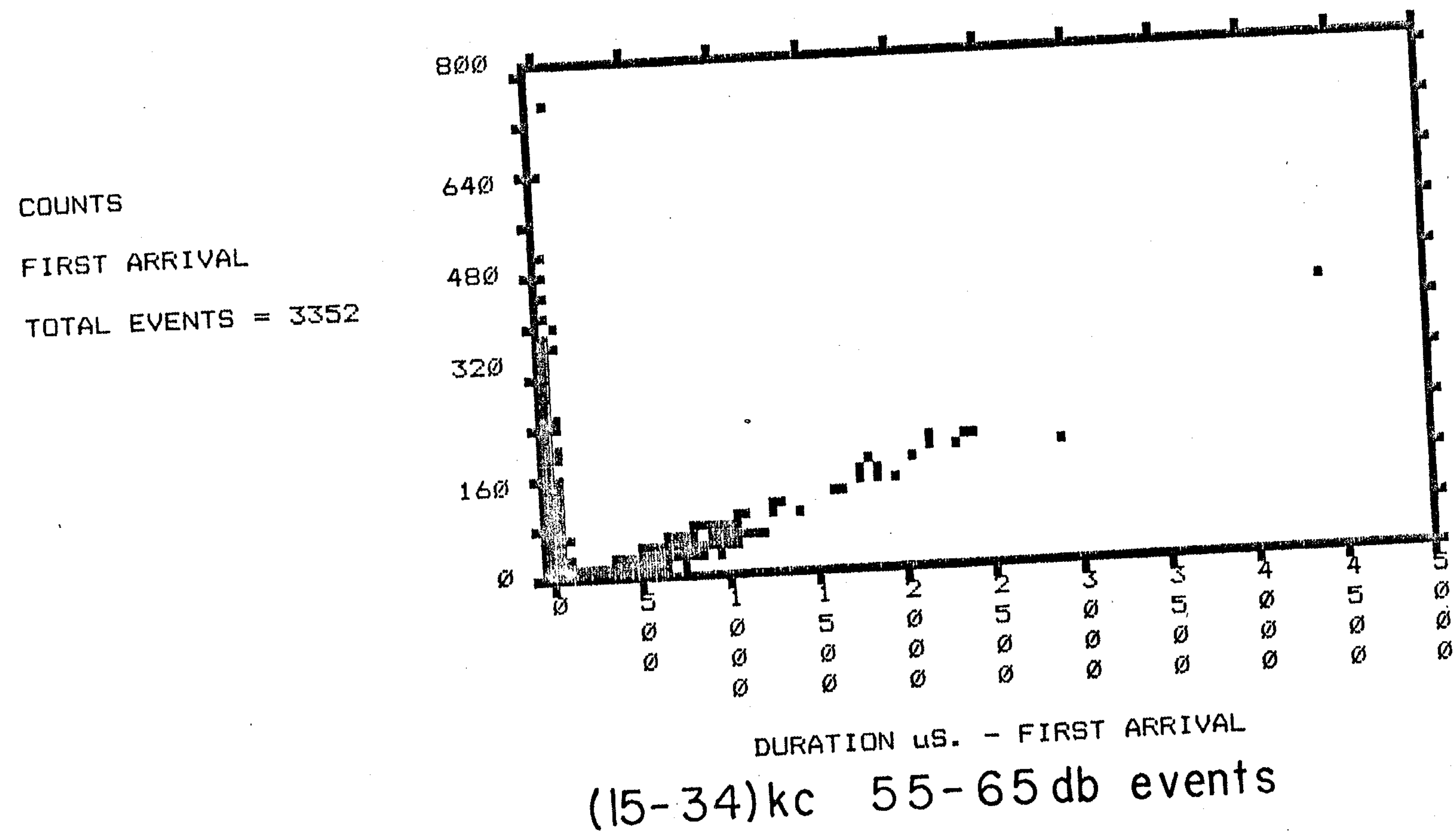

COUNTS
FIRST ARRIVAL
TOTAL EVENTS = 3352
800
640
480
320
160
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
DURATION uS. - FIRST ARRIVAL
(15-34)kc 55-65 db events

FIGURE 21

CONCLUSIONS

- K-JOINT IS AN EXCELLENT EMITTER OF A.E.
- AMPLITUDE BEHAVIOR CORRELATES WELL WITH CRACK FORMATION AND PROPOGATION
- RATE DATA CORRELATES WELL WITH PREVIOUSLY ESTABLISHED RESULTS
- POSSIBLE TO ACQUIRE DATA FROM COMPLEX GEOMETRY IN A NOISY ENVIRONMENT
- AE DATA MAY BE ACQUIRED FROM REMOTE UNDER WATER LOCATIONS USING COMMERCIALY AVAILABLE EQUIPMENT
- SIGNALS MAY BE CLASSIFIABLE

FIGURE 22

RECOMENDATIONS

- FREQUENCY ANALYSIS AND SIGNAL CLASSIFICATION
- STUDY OF SHAKER GENERATED ACOUSTIC EMISSION FOR A DAMAGE DETECTION MECHANISIM
- DEVELOP STATISTICAL DATA BASE OF A.E. BEHAVIOR FOR JOINT FAILURE
- TRY A.E. TECHNIQUE ON AN ACTUAL PLATFORM

FIGURE 23

observation, I thought was very interesting. It could be a good damage detection tool.

We have only studied one K-joint, acoustic emission on one K-joint. It's easy to draw conclusions and say conclusively what happened, but what would be much more helpful is further study. We broke two or three more, and we saw the same behavior. I could stand up here with a lot of confidence and say, "An increase in amplitude directly correlates to the onset of cracking or propagation," but we need a little bit more study. It would be a lot of use to people in the field.

And lastly, I think the State-of-the-Art is, the size of the equipment and the power requirements and the software available, you can actually take this and put a couple of probes in an offshore structure and get back good data. And if there is a failure, you may see something. So I'd like to try it.

MR. DAVIES: Just some general points. Was it a tension fatigue?

MR. FULLER: Yes, it was. It went from 0 to 10,000 pounds.

MR. DAVIES: You didn't go through a reversal, as such?

MR. FULLER: No, we did not.

MR. DAVIES: And the metallurgical condition of the joint, is that representative of what would be present offshore?

MR. FULLER: It's difficult for me to answer that question. I think you can get an answer, though. We have a lot of representatives of platform manufacturers here. They'd be able to answer that question. It's difficult to say what the metallurgy of that particular joint was, because you saw it had been stressed before, and it had a lot of rough treatment. So we didn't know. We didn't study that. It's a good question, however, but do you think that would make a difference?

MR. DAVIES: A great difference; yes.

The other thing is, if you had some way of segregating the emissions that occurred to determine the maximum loading part of your cycle, I think that would be a powerful way of separating the extraneous omissions.

MR. FULLER: You are probably correct; however, most people are not trained operators of any type of equipment. They need something they can plug into a platform.

DR. GREEN: That's pretty easy to do. We never did it with a K-joint, but a number of people have done it. It's pretty easy to discriminate.

MR. FULLER: It's true. However, I'm not saying that's incorrect, but what we did was load the K-joint in a directional fashion sinusoidal loading, very, very, very simple loading. It's very different to predict the load applications that a joint will see in service. That's not one-dimensional at all. So it's difficult to say what the maximum stress is in one direction.

DR. SUNDER: I have one question. What happens if you have reverse loading? Can you speculate on the reverse loading, or if you have additional bending effects?

MR. FULLER: We did a test like that. We get cracks that start on the other side. Our cracks grew along the inside of the crotch, if you will. If you have reverse loading, the cracks will start, from our experience, on the lower outside portion of the weld, also. So you'd have two failures. We'd had, just call it one failure. As far as acoustic emissions is concerned, I can't even begin to speculate.

DR. GREEN: I can tell you on a cantilever beam or something like that, in certain materials. Aluminum, I don't know, but with some steels, you can discriminate between the crack growth by a technique like Ray is talking about. If it's on an offshore platform, God knows when it's going to be maximum stress. But in the laboratory, you can do it, and you can discriminate between direct loads and direct welds for the materials that I am familiar with. You get crack growth. I thought otherwise, but my students proved me wrong.

So that's good, if you're looking for crack growth.

DR. SUNDER: The other comment has to do with the change in direction of the forces on a real platform. You might get a tension loading for a certain time and bending in a certain direction, but a few minutes later, it will be from some other direction. What would that do to acoustic emissions or ultrasonics?

MR. FULLER: That's a good reason to try it on a platform. It would be a lot cheaper to do it on a platform than to try to bring up some laboratory tests.

MR. BOLELHO: You will not get a crack on the platform.

MR. FULLER: I don't know about that.

MR. BOLELHO: So your last comment on doing that kind of test on the platform might not give you the answer you're looking for.

MR. FULLER: That's true, but if we don't put it there at all, we're certainly going to get no information.

MR. BOLELHO: You can also do that in connection with other tests as well. Apparently, if there is a platform, you try to get some joint, instrument platforms, try to get some of the answers.

DR. GREEN: You can include an artificial joint, but it would break, and then the whole platform would collapse.

MR. DAVIES: Usually in a platform offshore, people are concerned about pre-existing cracks. They just want to know whether it's actually growing.

This is my concern about discriminating frictional crack rub and actual crack growth, because if you go straight offshore, and I would hesitate to do that at the moment, and you get emissions. I really don't think you're in a situation yet where you can tell friction from the actual growth in the cracks themselves. So we are still trying to segregate the two.

MR. FULLER: I was not suggesting that. Only for study and background data, to see what actual real data looks like. Then we could design our experiments a little bit more realistically.

MR. DAVIES: I would also add that our experience is, we've done experiments on similar samples, the noise from the actual crack growth is considerably less than the noise from the friction mechanism. And I think Battelle's work is very much in agreement with ours.

DR. GREEN: I'd have to take issue with that, because Battelle finds exactly what I said, that the amplitude of the sound from a crack growth is greater.

MR. DAVIES: Obviously, it depends on the material.

MR. GREEN: Of course it does.

MR. DAVIES: Battelle has worked on material similar to the one we looked at.

DR. GREEN: There's one test not on the platform, but in an aircraft in Australia where there is a crack in the box beam, where the wing is attached to the fuselage, and Battelle Northwest is monitoring that one. And they monitor when that crack grows on aircraft flight. I know that's not offshore platform, but that's a case of monitoring a crack with a noisy background.

DR. BASDEKAS: One of your recommendations for the future is the ability to do thickness analysis. What mechanism are you suspecting that the massaging of the data can't reveal, that frequency analysis would?

MR. FULLER: First of all, the data is collected in a fashion -- the State-of-the-Art equipment, I notice, doesn't apply to research type equipment. It takes an event, calculates certain key features, I'll call them amplitude, energy, rise time, that type of thing, and stores that data, then absolutely disregards all other information.

So it is difficult for us to back out from the records we have exactly any character of the pulse that may be new or give new information.

So what we're trying to say is that acoustic emissions generated from a crack or some other critical mechanism, say, corrosion, will be different from frictional noise in some way. Now frequency analysis is going right to the heart of the very basis of looking there for a difference. And I think the last four slides I showed said that there was a difference in certain portions of the data. Now I am not speculating what that difference is, but we can look at different portions and see that they're different.

Now frequency analysis, FFT or some other method, can give us a handle on what it is. If it's good, we can test that on -- maybe they'd do an FFT before they start the data. That's what we've got to do. Chuck is, I guess, sponsoring someone.

MR. MCGOGNEY: That's our contract with United Technologies, to characterize the signals. That's the whole transducer. That's the start. You get a transducer. You get the information you want, and from there go on and try to process that signal. And we have a study going that does that. It's gone on for six months. So we've got another 18.

DR. BASDEKAS: To try to find some relationship between the frequency and distribution of the emitted signal is a function of, I guess, how close you are to the breaking point.

MR. FULLER: No.

MR. MCGOGNEY: Eventually, yes. We want to avoid catastrophic failure. First of all, we've got to know what it is we're talking about. Are these rubbing, or is this an actual propagation of a crack? Or is it some other intermetallic cracking? We have to come up with a transducer. That's number one. We have an idea on how the process goes.

DR. BASDEKAS: Once you have a very small crack, in the material, and you get the acoustic emission, that small crack volume, or void, is going to be used as a chamber, and once we excite the energy of -- the acoustic emission is going to excite that chamber and is going to resonate, based on its own volume. At the beginning, it is going to resonate at higher frequencies. It's like hitting a small bell. Once the crack gets larger and larger, the voids will be larger and any material failure is going to be like hitting a bell, and it increases the size of the crack, there is the possibility that the initial signal, which would be a high frequency, might have a frequency content which is going to be lower and lower, the larger it becomes.

So the frequency analysis might give us some indication how far along the line we are, in terms of what will be the size of the cracks that sort of resonate. That might be one way.

MR. MCGOGNEY: It's the zone at the head of the crack tip that concerns me.

DR. BASDEKAS: All right, but that's where the energy will be released, but the rest of the cavity will resonate. The larger the cavity is, the lower will be the frequency that you are going to get. This is a speculation that somebody could measure and find.

MR. COLE: Isn't that the random dec?

DR. BASDEKAS: Yes. This is one mechanism to find out if there is a frequency dependency, based on the extent of the duration or the crack growth.

MR. COLE: I gather your results get in a little later. Maybe that was because it was seeing lower frequency range.

DR. BASDEKAS: So there is some consistency of the stimulation of that mechanism.

MR. FULLER: The flaw that you are looking at is on the order of five or six inches long, and the flaw that Chuck is interested in is a thousandth of an inch long. You are not competing at all.

DR. BASDEKAS: No, but at the different frequency range, you might get kind of a shift to the lower frequency content, as a result of that acoustic emission.

MR. DAVIES: I don't want to sound too negative about the frictional noise from the crack. We still see that as a very viable way of finding cracks. All I am saying is we have to be careful to discriminate between acoustic emissions. But we have certainly found trends. Frictional effects are certainly related to crack growth. So I don't want to be negative about acoustic emissions.

Dr. Robert E. Green, Jr.
Johns Hopkins University
Acoustic Emission Source Location and Identification

DR. GREEN: The question we were discussing just before the break, is one we have been working on for three years. There has been work also going on quite extensively at the Atomic Energy Research establishment at Harwell and work at the National Bureau of Standards and work at Cornell University. Dick Williams is now doing it at United Technologies. There are five or six groups that are trying to characterize acoustic emissions, the sounds that come from known defects. It turns out that it is easier said than done.

(Slide) N.A.

Conventionally, theoretical analysis of acoustic emission signals in the past has assumed a situation like I have shown here, where if there is an internal source, it is assumed that the source emits a single spherical wave which comes out from the source and is then picked up with a piezoelectric transducer located on the surface of the specimen.

Since ultrasonics preceded acoustic emissions, and as best I know, all of the commercially available transducers, except the new ones that have been developed by the National Bureau of Standards which is just like the one that Dick Williams has at United Technologies, are all based on the fact that they took ultrasonic transducers, which were resonant type, and then since they didn't know what signals they were looking for, to make them broad a band as possible. They highly damped these transducers. That is why it is necessary to have a preamplifier right beside the transducer.

It turns out there are problems with this, as I will show you.

The other drawing I have here is if you have a surface source that may generate a surface wave, again, it may be a spherical wave.

Now, if you are familiar with ultrasonics and wave propagation in solids, this is an extremely oversimplified situation, and to make an analysis based on this situation is not likely to be too fruitful.

(Slide) N.A.

There are two types of emissions normally discussed in the literature. One is called a "burst" type emission, illustrated by A here. That is like a damped sinusoid. Then you have a continous type of emission, which many people now believe is made up of an overlapping sequence of these bursts. I would like to pay particular attention to this, because this is what is normally analyzed.

(Slide) N.A.

I have just drawn schematically here a more realistic picture. This is also oversimplified. Since I did this, there has been experimental work done by Page, Boddely and colleagues, both at the Atomic Energy Research Establishment at Harwell, and also at NBS, which shows what you would expect. If you have a source of a certain geometry, it will emit something other than a circular wave. There is no reason to think otherwise.

All other physical phenomena emit waves, depending on some type of geometrical shape. This is also true for acoustic emissions.

The second thing is, not only do you have that happen, some elliptical type case that I have shown here, but you also find that in most real structures, the material is anisotropic, meaning a rolled sheet, a piece of pipe, etc., that the wave speed is different in one direction than another direction. Therefore, even if you started with a spherical wave, initially, the wave will distort as it propagates, and it will not remain spherical in most structural solid materials.

Another problem you have is, depending on the frequency of the wave that is propagating, different frequencies will attenuate with different amounts because of the various interactions with the various frequencies with the material properties like grain boundaries or dislocations or vacancies or cracks. So it is a fairly complicated situation.

Also, for general excitation, you won't get a single wave. In an isotrophic solid, you will get a bulk wave. You get a bulk wave which is shear, and on the surface you get a surface wave. If you take into account geometrical conditions, you will get lamb waves, some other type wave, depending on the geometry.

So it is a fairly complicated situation, and you need not only to know something about the source, but you also need to know about the medium which it is propagated.

There was work done classically by Cutten and Orr, where they took the same acoustic emission source and used three different detectors. If you used a system like this, you expect maybe it might be a burst. If you used a system like this, you would think you would have a continous source.

So the first thing you have to worry about is what kind of detector do you have.

(Slide) N.A.

This slide is taken from the work of Dunnegan and Harris. The slide, on the left is a figure which I have seen more often than any other figure in acoustic emissions. This is based on claims that in their work, where they measured the acoustic emission count as a function of strain during a tensile test on an aluminum sample, the "events versus strain" which is essentially versus time, agrees with J.J. Gilman's model for dislocation mobility.

They claim, therefore, that it must be a dislocation source. If you look at all the other figures in their paper, including the one on the right, you will see that none of the other figures ever match up with anybody else's.

These figures have never been reproduced in any subsequent articles.

I want you to pay particular attention to the general shape.

(Slide) N.A.

Jackson and Azenblatter in Cologne did some work 10 years ago where they took a constant source, constant sensor and so forth, and they changed the threshold of it. In other words, they would take any count if it went up above a certain voltage.

If they took events higher than 3 volts they got the three curves at the top. If they restricted it to any events of over 30 volts, they got this.

So you see, by picking the transducers, picking the filters and so forth, picking the threshold elements, they could get a variety of curves.

(Slide) N.A.

This is a complication I spoke to earlier. This was done at the Admiralty Marine Technology establishment in England where they showed that if you have a single source, they convert into shear waves, longitudinal waves along with surface waves. You get such a complicated pattern that trying to analyze it is virtually impossible.

(Slide) N.A.

About seven or eight years ago, I was visiting the Bureau of Standards, and Frank Breckenridge, Harold Shea, and Mo Greenspan were doing some work. They found if they fractured a thin glass capillary or a little piece of lead -- in fact, Nelson Shue, one of our former students at Hopkins, has a patent on that.

They did a calculation where you have a set force, unloading or loading of a surface and, if you measure on the same surface, you get a surface displacement versus time like this. This corresponds to a P wave, a longitudinal wave. So you are breaking a glass capillary, measuring very closely the shear wave arrival time and the Rayleigh wave arrival time.

(Slide) N.A.

They used a capacity transducer to measure surface displacement in this case, and they got a wave form that looks very much like the theoretical wave form; the test block was made out of aluminum. Aluminum, I think as most of you know, is of the common metals, the most isotropic. Steel, iron is much more anisotropic. So you get much more propagated behavior. So aluminum is a pretty nice material to look at if you don't want to worry about too many complications in the wave propagation.

What they did, and we have done, is break a glass capillary to get a known wave form. This particular system is set up so that there is a piezoelectric crystal in here which you can calibrate by an MTS machine so you know what force is applied when the glass breaks.

Then you can pick it up with the transducer on the same surface. And I am going to talk about laser beam transducers that we use either on the same or opposite surface.

(Slide) N.A.

The wave form that is recorded by Breckenridge, Shea, and Greenspan uses a capacitance transducer like this. You see it is very good compared with a theoretical wave form.

I was amazed because I never saw anything so reproducible in acoustic emissions in my whole life.

(Slide) N.A.

Dr. Palmer, in our Electrical Engineering Department, as well as other people, has been looking at surface wave devices, and he used laser beam probes to pick up those surface waves.

I asked him to make me one to try for acoustic emission. This is the simplest one that he made.

Essentially, you have a laser beam going through a beam splitter hitting the surface of the specimen, coming back into the detector, and the second beam comes down, and the reference mirror throws it back into the detector.

The standard practice now is to put the reference mirror on the piezoelectric crystal so you can monitor the low frequency vibrations.

(Slide) N.A.

Using this system and breaking the glass capillary on the aluminum block, measuring on the same surface, using the optical sensor, this is the wave form characteristic of the source. These big oscillations here are resonances in the block itself.

B shows what you obtain under exactly the same loading with the commercial piezoelectric transducer. All of these things here are resonances in the transducer.

(Slide) N.A.

If you put on a longer time scale exactly the same information, this is the wave form characteristic of the source. This is due to interactions with the specimen on the table.

This is what you get with the conventional acoustic emissions transducer. I ask if the threshold level has any meaning. It may, but I am not quite sure what it is.

(Slide) N.A.

The reason for this is that a standard commercial transducer looks like this. There is a wear plate usually made of some surrounding material.

In standard nondestructive testing practices the piezoelectric element is in there. There is generally some plating here, and some cheaper companies don't even bother with that. They put a little piece of aluminum foil in there. They don't even put it all the way across. They put it in the middle of the thing.

So when you look at the beam, you get two beams instead of one. The backing in some, to make it broad-band, is epoxy loaded with tungsten in the backing of this.

Nevertheless, all of these elements have their own resonance profiles. So they contribute to these oscillations.

(Slide) N.A.

As a result of this, and having the optical probe, we decided to try some experiments to see if we could characterize the mechanism of emission. It is a dilemma in a sense because we would like to be able to see where the sound comes from. That means we want a small specimen so we don't have to look so far.

On the other hand, the general amount of energy released from the emission is volume-dependent. So there is a tradeoff. If you go real small to look at it in the electron microscope, we are reducing the probability of getting a big emission.

It is a difficult problem, but at least in some cases there has been success.

This is a little micro tensile specimen. Actually the new ones are turned around so that this is the probe rather than this long side here.

I won't go into the experiments we did, but the specimen geometry didn't modify throughout the signal.

(Slide) N.A.

The latest laser interferometer I have is made by Dr. John Murphy of our applied physics laboratory. He has made about three or four of them for me. Each one gets better and better.

The particular one I have now has a set frequency response of 0 to 60 megahertz, noncontact.

Here is a picture of it on the microtensile machine. In here is the little specimen. The pneumatically-driven machine is very, very quiet. I stopped doing this work once because I couldn't find a machine that was quiet enough to let me do it.

The next day they found one. There are no metal-to-metal parts rubbing against each other.

The laser beam shoots out here into the specimen.

(Slide) N.A.

This is a picture looking from the interferometer at the specimen. You can see the laser beam is in on the specimen. We put it just above the gauge line because if you put it at the gauge line the microstructural change will also cause the surface to upheave and change, and you can't tell the difference between the surface motion, due to the deformation of the material, and the wave form. There are also some very nice specimens made at Harwell. They are hemispherical specimens, with the gauging underneath the hemisphere and then a tensile specimen. So when the sound is emitted, it propagates through the hemisphere and comes out at the top surface. We have done work with those also.

(Slide) N.A.

This was an experiment done in 304L stainless steel. That is one material I am sure I know where the emission source is. Bill Brucci, who is now at Aberdeen Proving Grounds, did this experiment. He did specimens like I just showed you, and he found some low frequency oscillation here. Then he ran a 7-1/2 or 8-1/2 megahertz sound, much higher than it would normally be. And he found this grouping.

This is the grouping I want to talk about.

(Slide) N.A.

If you look at the specimen under the electron microscope, this is the specimen where he ran it down to the gauge line. Because of no other mechanism we can find, we assume that

that causes the low frequency measurements which almost everybody else does, too.

(Slide) N.A.

Here is a closeup of that. So you can see the lines that are diagonal within a given grain.

(Slide) N.A.

Just before the specimen fracture is where you get the higher frequency emissions. This is the entire fracture surface. It looks kind of like Swiss cheese or something.

(Slide) N.A.

If you go to higher magnification, you can find the holes. Some of these grow. Brucci, when he was a graduate student, counted them all up. He found a one-to-one correlation between the ones that broke and the high frequency emissions.

This lead him to suggest that they consider putting energetic particles back in their metal so they will break at a given stress level and we will know what the sound is.

I was pretty much laughed out of several metallurgical meetings with that suggestion.

But Stewart McBride of the Royal Military College in Canada has some better connections that I do, and he is having aluminum alloys made with different sized energetic particles being put in them. He has also just purchased an interferometer like mine. He is going to try this experiment, which I am looking forward to participation with.

(Slide) N.A.

The new transducer that was built by the National Bureau of Standards, which is certainly very small -- Chuck McGogney had one yesterday that was made by Dick Williams -- is phenomenal in its response. It does pick up the true wave form, unlike the standard overly damped ultrasonic transducer.

We have checked every transducer I can get my hands on, and some of the commercial ones are not so bad. I don't know what determines that. The manufacturers won't tell me exactly. Maybe if I tell some of them theirs are better than others, they will tell me how they made theirs. There are a lot of them that are terrible.

It is a very simple transducer, just a little piezoelectric cone. That is all it is. The idea is that you get a wave form coming in. If it is a small size, there is no phase cancellation in the different parts of the piezoelectric element. The burst goes in and is picked up, and before a reflection comes back and you get multiple reflections, you have already got the first signal. That is not a major change.

After I saw this one, I dashed out and tried a phonograph needle pickup, and it didn't work.

(Slide) N.A.

Here is a transducer like one of the first ones made, and here is one like Chuck had. It is in a plastic envelope. You use it with nonconductive materials to make the electrode, like the one Dick had.

(Slide) N.A.

This shows the wave form of one of those transducers, and you can see it is pretty good for the breaking of the glass capillary.

(Slide) N.A.

The second part of the work that I was interested in -- we are still continuing with this. We just completed some work for the Naval Sea Systems Command on high-yield steels. Unfortunately, the emissions are not as great from those steels as they are from stainless steel, but we have used it on titanium and aluminum alloys with this technique.

But the question arose, too: suppose you know the wave form and you have a funny geometry. Even if you know the signal, how far away could you pick up that noise?

So to make things pretty simple, I have a very good graduate student who is a whiz with computers, and he did a sphere. It is easy to calculate. Seismologists have done that.

The trouble is we never had a good way of testing the sphere. He did the calculations.

He wanted to work at Lawrence Livermore for the summer. They have got three Cray computers out there, and he never came back.

I learned my lesson on that one. So in any case, I decided to do some experiments. So I had one of the students go to the shop and grab some aluminum pieces of different shapes. He did a right circular cylinder, a cylindrical pipe. He did an I-beam and a solid rectangular beam as well.

Basically this is what he did. This is the specimen. It is 6- to 10-feet long. We put the glass capillaries on the surface. With the glass capillaries, they are not all going to break the same all the time. So we put a Bureau of Standards probe here, and we only have one good optical probe. So we used the signal we picked up with the Bureau of Standards probe as a reference signal.

Whenever that looked good, we would take the optical. Whenever it didn't look good, we would just break another piece of glass.

Then we also moved the optical probe down the beam, and also moving a second Bureau of Standards transducer down the beam.

(Slide) N.A.

This shows the experimental setup. Here is a Bureau of Standards transducer sitting on the end of the right circular cylinder. Here is the loading that breaks the glass capillary.

(Slide) N.A.

You can see it across there. The laser beam comes through there. What you do is you break the glass. If this signal looks good, you then take either the laser beam signal or another Bureau of Standards transducer. So we are looking to have the thing propagate down the surface of the vessel. The interferometer is on the track.

(Slide) N.A.

This is the wave form, according to the Bureau of Standards transducer. It is two inches from the glass on the surface of that right circular cylinder. There is still a physical body that still resonates. There is also still a cylinder.

(Slide) N.A.

If you go two feet down from that source, you will see that the wave form goes like this, and all you can tell is your radial wave; you can't pick up the longitudinal wave nor the shear wave.

If you look at this, you will find that the waves are reflecting from the ends of the pipe.

(Slide) N.A.

If you do the optical technique, you do the same thing again. You can blow this up a little bit.

(Slide) N.A.

And if you go two feet down, all you can see is this pipe. If you go to the pipe one foot and you can't recognize the signal anymore -- like Ray, I don't want to be negative; it doesn't mean it is no good. What I am saying is in certain cases it is going to be very difficult to tell what the source was because the signal is going to be modified by the geometry of the piece and by the metallurgical characteristics of the piece.

But the fact that we find anything is good, in my opinion, because then, by using appropriate triangulation and source location techniques, you can go back and maybe use ultrasonics or x-rays or acoustical holography, some other technique to tell you what is going on there.

You also may be able to just look at the amplitude of the Rayleigh wave, or you may be able to do -- if you are looking at frequency analysis, once you find out what your frequency spectrum is, as you expect, over large distances the high frequecies drop out, and you are obviously propagating the lower frequencies.

So we haven't done an exhaustive survey. We are still working on that.

We are very interested in Dale Collins' work, also the work that Haydon Wadley is doing, because we would like to see wave forms all around a given source, not just around one location that is probed.

One of my own students is using holography techniques to try to improve the resolution of the whole field technique for measuring surface displacements. That is sponsored by ONR.

Normally, when you look at holographic interferometry and you take an image of something, there is a hologram of it and you do that image at the specimen.

I should have said the sensitivity of this interferometry is a fraction of an angstrom; theoretically, it should be down to a thousandth of an angstrom. The limiting factor is the laser itself.

The one I showed that Dr. Murphy built, compensates quite a bit for the fluctuations on the laser itself. He used a different polarization of the two components. But, a fraction of an angstrom displacement is often the size, or less, of the acoustic emission system, versus 5- or 6000 angstroms, or maybe 3000 -- something like that. It is two or three orders of magnitude.

We would like to have some full field method that we could just pick up the displacement as a function of propagation distance, and that would give us a better handle on what is really going on.

In closing, I would just like to say that I started off into acoustic emission work from working in ultrasonics, because all the acoustic emission enthusiasts told me I should throw away ultrasonics. I was very negative about acoustic emissions, because the very first work was done by Scofield up in Boston. He used an anechic chamber, and he deformed a piece of aluminum, using thermal expansion copper. I thought, "That is nice, but it is not very practicable."

In the 1960's, the work at Lawrence Livermore brought that into fruition.

Unfortunately, many commercial vendors have oversold emission devices. Some of them are horrible. They don't do anything like the commercial vendors say. That is why acoustic emission is fairly unpopular among the same people who were enthusiastic about it.

Now I find myself a big supporter of acoustic emissions. I haven't changed my position at all.

The work that Mike showed looks very encouraging to me as an initial step in doing work with offshore structures. I think some combination of acoustic emission with random decrement or the flexibility monitoring or other techniques, like most combinations, are very useful.

We combined ultrasonics with acoustic emission in the laboratory specimen, and we found very similar effects.

A sound wave going through a piece starts getting scattered out, before you get a reflection back from a big crack, sort of like an early warning. At the same time, depending on the material, you get acoustic emissions. So they are very complementary techniques.

MR. DAVIES: I just wanted to ask you about the standard acoustic emission source you used?

DR. GREEN: As you know, the gas jet is good for the white noise. I still think that the glass capillary and the lead pencil is the easiest source. Haydon Wadley has done the laser. At the moment we have a great interest in cooperating with the Bureau of Standards. They're looking at the sparked electron beams. That's been done before.

Nevertheless, there are problems, because if you spark to the surface, it makes a little crater, and the next spark doesn't go to the same place. So there are some problems with that, but I would like to have a source I can dial on a dial and make any wave form I want, any rise time, any frequency that I wanted to do and put that in.

It would help me, to know, for example, like I know pretty well what happens with the crack. If I wanted to calibrate a system with that or have a crack developing in an offshore structure, I would like to do that.

So that's one of the problems. We'd like to have a better standardization, but I feel that acoustic emissions is going to make a revival, in the sense that I think it's going to come back on a better fundamental standing than it has been in the past. Ultrasonics went through the same cycle. I think acoustic emissions will also find its place.

If you know where there is a crack, I don't see anything wrong personally about putting a transducer permanently on a piece. Transducers, if you don't buy commercial ones, can be put on for $15. You could make this one right here for almost nothing. They're selling for thousands of dollars. The main problem, in my opinion, would be putting them on and then having the wires coming out. The wires may break or something like that. But I don't see that that's too horrible. There has been telemetry. They did put acoustic emission transducers on a bridge and telemetered it back down.

There are certain possibilities that you may not need the wire.

MR. MCGOGNEY: One of the things we are getting to is to pick up this information processing.

DR. GREEN: I think the faster you can get the transducer recording, the better. There's a lot of people working on that also. So you just do the best you can, but I think you identify the source and where the sounds are coming from.

If you can get the frequency response like Mike was talking about, then you might get some narrow bands. It's cheaper and easier to do. I am sure in come cases you can do it. In some cases you're not going to be able to.

Dr. H. Dale Collins
Battelle, Pacific Northwest Laboratories
Application of Acoustical Holography to the
Inspection of Offshore Platform

DR. COLLINS: The work I'm going to talk about was done around six years ago. It was reported to the OTC in 1978. Essentially, what I'm going to talk about is an imaging system. We've talked about low-frequency systems, as far as the modal flexibility analysis and also random dec, but now we are going to talk about looking into the weld material itself and getting an image, using digital reconstruction techniques.

Now when we built the system, we had to worry about the environment of the North Sea, and we had to worry about temperatures on deck, temperatures in the water. We had to worry about pressures up to 500 psi, down 4000 feet in the North Sea.

We made our own fully flexible two-dimensional sensor array that conforms to a pipe. So you get a two-dimensional image which was actually three-dimensional, because it went through 32 planes in the volume.

So essentially, it produced a three-dimensional image in real time. Typically, the image contruction takes about a second.

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Here was the concept of our first device, a portable device. The second device is actually a fixed device on the platform, with a computer on board. And it integrates acoustic emissions with acoustic imaging, but that's been proposed and has already been worked on.

This was the concept here. This gun is not only an acoustic gun, but it has a television camera mounted right here, a television with a tungsten halogen light, which gives you an optical picture of the weld structure. This is the acoustic array of 160 elements, flexible, five rows of 32 generating real time images. The 160 element array would conform right to the curvature, so you don't have coupling problems.

Now, all that's required of the diver is to just move this around this complex structure and it interrogates this complete weld and gives you a picture of the inside of the weld and the surface. It gives you an external picture with the television, so you integrate the two views on a television screen. You can then read all your data with your computer, you've also got your inside picture of the weld, and you've got the outside. That's all your data.

Now this was a modified Perry submersible. The inside operator here has a viewing screen, and everything goes on digital tape and can be reconstructed at the surface. He sees the reconstruction immediately. You can take all the data back to the surface, and the president of the corporation can look at it himself.

Now also, the diver's gun has an LED array on the back of it, so the diver gets a view of the image also to help him. So it's not just a dumb device. It actually helps him when he goes around. He can see the flaw come on, and he can tell where he's at, and the operator in the sub doesn't have to tell him what's happening.

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The image on the screen is displayed on a B scan, a C scan or any rotation tilt you want. Once it's put in the digital memory, it regurgitates it over and over again.

Here's the gun itself, showing the geometry of the gun. Notice it's five rows of 32. That's the flexible transducer array element. I'll show you that in more detail. It's skip bounce imaging. You're actually focusing 32 planes through to the weld zone.

Here's the television camera that has the tungsten halogen light, so that gun has a waterproof pressure vessel.

DR. GREEN: What's the coupling? Is it water?

DR. COLLINS: Yes, it's direct contact. The water's all around it.

DR. GREEN: But a thin layer.

DR. COLLINS: Yes. That's the one thing I never have a problem with on this.

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Here is the gun with the LED array, the matrix array of transducers, the TV, the tungsten halogen light. This is the diver. He also has a pack that he wore, a diver pack, and on it was the various processing: 160 power amplifiers, various signal processings. I won't go into that too much.

On board the submarine was all the processing for the video image, the solid state memory, 3-d rotation tilt and the rest. So essentially the system I'll show you is not a very big system. It had to go down in the submersible. It had to operate on very low power, because the submersible operates on batteries, and they don't like using all the batteries.

So we really had some very terrible requirements.

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Essentially, what we did was, we electronically shifted and focused 12 transducers at a time. Actually, we started with six and built it up and moved to 12 across here and interrogated this volume. Then it would shift back. So what we had was an electronic sweep, using a focused holographic mode, all digital.

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Here's a picture of the flexible array. The transducers are single transducers for imaging, and they're mounted in elastomer, so they can flex and twist, so they will conform to a certain radius of curvature. We make them so they'll go with the range we're trying to inspect.

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Here's the elements we make. We design and make these transducers ourselves. It is essentially our PZT-4. Now this has to withstand seawater, it has to withstand pressure of 500 psi. It has to be pressure cycled, thermal cycled and selected. So once you get your array, it's reasonably expensive. There is the equipment as it stands. There is the LED array. There's the gun television camera up here with the tungsten halogen light. The acoustic array. It also had magnets, so when we put it on there you pushed a button and the magnet conforms the array.

Here's the acoustic control box, the display control, and here was the controller. These three boxes went inside the submarine.

This dial here, you just dial for 32 complete scans through the metal automatically, and it shows you on a B scan exactly where all of the flaws fall, or you can set it on any plane you want, any depth, and it will stay right there.

So essentially, that's all it really has to do to set the system up. It's an imaging system and has high resolution. Those are all waterproof boxes and the rest of it.

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In fact, we bought these boxes here, we bought them from Piper Products, just because they had a good reputation.

Now this was our noncommercial cable before we got on there, but it shows the device on a piece of three-inch platform steel. Here was the diver pack without the commercial cables. This weighed about, I think, 15 pounds.

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Here's a picture of the LED array showing the gun from the back, and we put a little C-scan picture in the front right there so that the diver can interact with the device.

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This was the data acquisition system and the data playback system, so that we could acquire all our data, record it, take it to the surface and replay it right on the surface. This is what the platforms owners want. They want to be able to see exactly what happened, so they can evaluate their own data. They don't like somebody telling them that they've got problems. They'd like to see it themselves.

This is a requirement of ISS and the platform people.

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I'll show you some pictures later of some of the holographic images, but I want to talk about another system now. This is a system we designed for British Petroleum. This is a system that stays right with the platform. In other words, we don't have the problem of the submersible. It monitors the platform day in and day out.

Two concepts here -- Wintermark did an analysis on platforms, where they identified on the platforms what you call "hot spots", but really are pieces where the stress was concentrated. They're the high stress points of the platform. Then he said, if we would implement some kind of inspection technique to interrogate the high-stress joints, that would be kind of a nice system to have, a system we could live with. So I am not advocating that you instrument every joint. You pick the joints with the potential high stress you feel will have failure and you instrument them. You can't instrument them all, but that's not the purpose here.

We actually put these arrays inside and telemeter the data up. I've got acoustic emission sensors also. The acoustic emission sensors will listen. When they hear a lot of activity, then they will tell the computer to look at this joint more actively with the ultrasonics.

Typically, this system goes around all these joints in sequence and alarms if a crack is growing to great magnitude. It always tells the operator where things are, and it has appropriate alarms. The acoustic emission here is to essentially weight the inspection to that joint.

This system can be very reasonable, because these arrays can be built very reasonably. It can be put on at the time of construction or it can be put on at sea. But also, this system would be very nice because everything can be programmed. You can do your crack analysis, dimension analysis, fracture mechanics, dynamic crack growth, on and on. So you have a very nice system monitoring your critical points.

You can also image with acoustic emissions. This is one of the new things we have been doing. We have been doing acoustic linear time of flight holography with acoustic emissions signals. However, in this system you integrate both the acoustic emission and the acoustic imaging technique.

VOICE: Did you say you built that, that was a project you had for British Petroleum?

DR. COLLINS: It hasn't started. It just leans on the technology we developed before, though, the same type acoustic array, and then there are acoustic emissions systems we have built, also.

But typically you would have the critical joints being monitored, going up to a computer with the data link-up, and processing all your data that way. That would eliminate the submersible, which was a very costly item. In fact, Northern Offshore went out of business because they invested in too many submersibles.

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I want to show you some resolution imaging. We do a lot of acoustical work. We do a lot of pressure vessel imaging, also. We just delivered a system to Electric Power Research which we had some demonstration runs in Connecticut on 10- to 12-inch thick steel.

So I just want to show you some images, also, of some of the resolutions you can get using acoustical holography. People always think of holography as a coherent type situation.

We just measure the time profile across the array, which we convert to phase by which is speed. We calculate the phase. We use several algorithms, but the most popular one is the backward wave propagation algorithm. This means to sample the field at some point, X,Y, out here, and take the Fourier transform of the field which gives you the angle's spectrum. Multiply that by the back propagator. All that does is decompose the waves into a series of plane waves.

So your backward propagator is just a phase propagation back. Multiply it by a back propagator for all these angles, and it propagates a wave, right back to the source, and when the wave gets to the source, it's the source itself.

That's a beautiful algorithm, because it's very easy to do digitally. Use an array processor. All of these are being done, essentially, in real time, not hours of calculation.

So what we are talking about are one-second images, or less than that. A requirement in all our images is to strive for real time.

Here's typically a piece of aluminum. You can see you're about 10 cm down. You are looking at shear waves. Now, shear wave imaging is much more difficult than L wave. L wave is easy to do. Shear wave images, with their aberrations and everything else, are not that easy to do good imaging on.

Typically, we set up the spacing requirements and the resolution of our system -- the holographic resolution. Essentially, when you do the calculation, you really come down to the Rayleigh criteria. The Rayleigh criteria for incoherent sound is different than for coherent sound, but just bear me out.

These systems are typically f4 systems, so your resolution is 4 in the lateral direction, and the time of flight is the transit time of the pulse. If you use a lens resolution, it's the F number squared. Now, we are looking down in the reconstructive images. These are all digital econstructed images. There is nothing analog in this system.

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Here is the Frenel hologram. It's typical. All it is is a series of diffraction lenses all integrated into one super-position.

Here is the reconstructed image. Notice, you can size each one of those holes. This is the separation. Here's 2 mm. We are using 2 megahertz, which is about 120 mils or about 3 mm L wave, and about half that for shear wave and metal.

Once we reconstruct the image, and put it in the memory, then we can regurgitate it in real time. These images here, you can rotate and tilt in real time. In other words, you can rotate it to any angle you want.

Here is the staircase showing the depth: here's the lateral scale; here's the background; here's the shadow on the background. And you can rotate. If I had the tape here, you could rotate and tilt, in real time, to any aspect you want.

This is a holographic image.

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The other thing I would like to emphasize is that our holographic image processor has the ability to integrate up to 10 images, actually take holographic views of steel or whatever it is and integrate those images. That's not like isometric imaging, which people know about. It's actually taking views at different angles and actually integrating them into a three-dimensional system.

This is what our system does. I will just show you a simple one here. Here's two objects of different depths. Typically what we do is we make a hologram at each depth. We reconstruct each image, put it in the memory, and then we regurgitate it in real time.

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This is an image of an actual crack at the bottom of a seven-inch solid piece. It's aluminum here. You can see, now, the nice reconstruction image of that crack. After it has been put in the memory, you can rotate and tilt it. Vertical view, side view. This is about an inch long, or 2 cm long.

The other thing I was going to show you is integration of images. It would have shown those two images very nicely on one image. You would be able to rotate and tilt.

This is a picture of a crack and you can see, even in the background, the shadow that you get. Let me shift gears a little bit and talk about acoustic emission imaging. Here is, essentially, our theory as far as acoustic emission.

A typical crack, let's say, would start propagating, as a series of acoustic point sources. Now, as it cracks, it would emanate a spherical wave front. You would have an array out here, and essentially, we are talking about 12 to 16 transducers. That seems to be fairly sufficient to get a reasonably good image.

We put 12 to 16 transducers out here and we measure time of arrival, with respect to each transducer. We get a time profile across the aperature. It's a phased profile. Essentially, what we get is the function of a lens. This is what we call time of flight holography. We are really converting to phase. Then we take the sine and cosine for both the real and imaginary, and do the computation.

This is a linear hologram, though. What this will do is actually image what the source looks like at any time. Any time the crack emits, this receiver gives you an image.

Now, you say, "What about other acoustic sources over here, around here and back over here?" The image will only correlate when all points correlate together. It's a matched filter, at this point. All the noise automatically gets filtered out because it's only going to reconstruct if all these points add up at the right time frame.

That's actually what imaging is, anyway. But I just want to show you, if you had a normal AE system with three transducers, what you really have is a sparse filter -- a sparse aperature. So you can't expect too much resolution out of that.

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Holography is probably the most simple algorithm to use and it's one of the most efficient algorithms. It's much more efficient than synthetic focusing. In synthetic focusing, you have got to go all the way through the material, focusing all the way, hoping it lies in one of those places. Holography tells you where it's at, and you only focus where it's at. Typically all you do is record these blinks, or events, in time. Each time it blinks, you record the time profile across the array. All it means is you have transducers here with start and stop clocks. The accuracy you want will depend on the clock frequency you want.

So each one has a clock. You get a time profile. That's converted to a time of flight profile. It's converted to a phase image. Bang. Real-time image. So as the emission progresses -- let's say you have a fatigue crack, this will show you what a fatigue crack looks like, acoustically, the image of it. You can state both the lateral and depth resolution, because when you get this array in close to your source, you can have an F number of less than one. That means that depth resolution is better than the lateral resolution.

So here's an analytical tool which you can use. Also, the propagation algorithm lets you look at the wave front and tells you what the wave front is, and how its propagating into any point. Anyplace you are reconstructing will show you what this wave form looks like. There's a very powerful technique for understanding how intergranular stress cracks differ from fatigue cracks.

Now, you say, the image may not look like the cracks do physically. That may be true. But most of the time we have pretty good correlation. Even if it doesn't, it tells you how they grow.

So the system is very simple -- clocks, transducers -- and we make our own transducers. They are very cheap -- a simple mini or even a micro.

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Typically, if you had a point source out there, you would get a typical phase profile like this. Now, take each of these points and take the phase and convert the phase, and then take the sine and cosine, which is essentially the real and imaginary parts of these.

Then do the back wave propagation reconstruction. You don't have to do that. You can do the Frenel if you want. But here's the reconstructed image. The intensity of the reconstructed image (those are the three dB points) typically is the resolution of your system. That typically correlates with the theoretical prediction. There's an actual acoustic emission, the signal processing, right there. And there's your signal.

I am not saying that you can get it on every material. Here's a tool, though, that can be very interesting to do some analysis with.

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Here's one system that we hooked up and had a fatigue test on aluminum. It's nice and clean. So that's what we started with. I will show how some of the reconstruction algorithms we used on this worked.

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The concept is very simple. Place the array near a suspected area of concern, paste it on, leave it, and just monitor. Then, let's assume that the crack starts at the bottom and propagates up. As soon as it's started to crack, it receives the signal and you reconstruct. As it propagates up in time, it builds a series of point sources like this.

So over a period of time, when you build up a crack, if you image the crack it would look like a bunch of points, it progressively grows up through the material. That would be the C scan here, but we can also give you an isometric view of the intensity function, which is kind of nice. We do both of those.

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There's typically the pictures of it as we are reconstructing it, building up.

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There's typically what one would look like, and if you image that, it would look like a line. If you took your limiting right there, it was a nice, bright line. If you looked at it in this intensity function versus distance, you can see it looks like a crack.

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The nice part about it is that your resolution is definable in terms of wavelength, object distance aperature, and that's very powerful, because it tells you how well you can image that crack. It brings out the frequency and the wavelength.

VOICE: Do you make a model that can be used in fabrication?

DR. COLLINS: Yes. In fact, that's one of the jobs we were doing for a Norwegian firm.

This is where our main emphasis used to be, in plants where they have large castings and forgings and things like this, and this gun is a very useful device. It's portable and it gives you an image, 3-D, tells you the flaws, tells you what size it is, and it's real time. It's simple.

DR. BASDEKAS: Can you indicate how marine growth might prevent you from using that on all the platforms? Do you have to go and clean it first?

DR. COLLINS: That's right. You have to clean the platform. We were working with Oceaneering, which is a big diving firm, on this project of looking through biological growth, mainly for surface cracks. There is no magic. But any critical joint, they will clean. That's not the problem.

DR. BASDEKAS: Do you have any feeling whether the offshore platform owners can reduce or eliminate marine growths so your device can be used?

DR. COLLINS: I thought I heard a paper on cavitation cleaning, but Oceaneering is looking for a cleaning technique. If you've got a cleaning technique, they've got $100,000 of money that's available this year -- they're in Houston, Texas, but that's a big concern.

MR. BOLELHO: From where is the technology available?

DR. COLLINS: This wasn't a model. This actually operated. The French took this to France, put it through its test and did a very nice job. They compared it to typical detection schemes, and it had the same detection capability as normal UT-type techniques. I had nothing to do with it either. They went through trials in a big sea water tank, and they actually took it out. It was a CONOCO platform. But when they went bankrupt then they got cut off, I kind of lost track.

I hear International Submarine Services is back in action, but I don't know what the status is. As far as the gun, I heard they had it for sale when the company went bankrupt. I won't tell you the price.

MR. SMITH: I'd like to introduce another one of our researchers, Mr. Alan Gordon. He's working on another system for us, and I'd just like to have him explain the concept.

MR. GORDON: We're doing something different in that we're looking at standoff inspection. The idea is to get a course view of the entire structure, to look for things like bent members, missing members, sawed-through members, rather gross defects -- to be able to look for those in a cost-efficient manner.

The particular sensor that we zeroed in on is a lens acoustic imaging system built by the Navy. It was built and hardly tested at all, it is on the shelf, so under the sponsorship of MMS we've got that rehabilitated and have done a couple of tests -- pierside tests. They've also got a couple of towers off of Panama City, so we can do very realistic in-ocean testing. We did run tests off the towers there. We lowered the thing off the side of the system. It uses a one-meter acoustic lens.

It's a very large objective lens and consequently should have fairly good resolution. We lowered it 40 or 50 feet, and we did get some images of K-joints that appear viable so far. However, the track history of stand-off acoustic imaging systems as opposed to close-acoustical imaging systems, we generally operate where the wave length is substantially smaller than the size of the structure.

Acoustic systems in general have had these types of problems, so the quality of the kind of acoustic images that we ultimately get is in question.

However, we did see these things. We've had some equipment problems out there, but the equipment problems are being taken care of and we have to run some more tests again on the same towers.

The idea is to be able to have a system, let's say in one day that will be able to image all the members of the tower and just go up and down. It will be launched from a barge. The system is roughly one meter by one meter by two meters. Hopefully when we put some propulsors on it it will be lowered by a barge standing off from the platform -- maybe 30 to 50 feet.

It has a range of 100 yards; it can image from 100 yards and lower down. The propulsors will hold it in orientation and we'll just scan all the members on one face, go off and do that again, and have image of the entire structure.

DR. BASDEKAS: Is Don Fold involved?

MR. GORDON: Yes. He knows what we're doing, he is not directly involved.

General Discussion of Methods

DR. DAME: As a summary of this workshop I would like to initiate a discussion of various opinions of each of the methods presented these last two days.

DR. DAVIES: A very general point. It seems to me that the objectives and capabilities of these methods are very different, ranging from detecting complete dismemberment, as it were, to detecting very, very small cracks. I wondered if we should discuss just what the different objectives and directions are.

There is a complementary role, I think, for many of these methods. You would use one method to do one thing and another method to complement results. I would like to see some sort of discussion. They are not really competing for the same task.

DR. DAME: That's true. I think each one has its own niche. Some of them are overlapping, some of them may be redundant in some applications. Some may indicate initiation of damage, which may not be of major concern to users. The people on the platforms may be more interested in damage that indicates structural degradation. I think each one has its own particular application, but I think you'd have to address that categorizing question to each one of the individual research groups.

MR. MCGOGNEY: As far as bridge structures are concerned, when I first came with the Federal Highway Department 13 years ago, I thought we had to inspect every inch of steel on the bridge, but later on, as the case histories have shown, we've started to categorize the details, so we've got categories which we don't even look at anymore because they're not significant.

Getting the more significant ones where our problems are, is where we want to look.

MR. DAVIES: If it were possible from this meeting to come out with a table of the methods and what it's aimed at doing and perhaps get general agreement on that.

DR. DAME: Why don't we walk through some of them and talk about what they can and cannot do? Let's take some of the structural analysis techniques; Random Dec for example. What is its purpose? Can we say that Random Dec is a technique good for crack initiation? Would you think, Hank, that it's fair to categorize that technique?

MR. COLE: Yes. I think a lot of these methods do the same thing. If you took random dec as a means of analyzing a signal, the higher the frequency you can get a good signal; you can always improve it, it's just another analysis method for measurement. But I'd say the higher the frequency you can go, the smaller the flaw you can find.

DR. DAME: So perhaps the scale should be crack size versus frequency of the technique. That would be one way. Random Dec is sort of an intermediate to high frequency but not ultrasonic or acoustic-emission range.

MR. COLE: We're doing some work now where we're trying to move it up into the 50 to 70 kilohertz. I'm not prepared to talk on that.

DR. DAME: In terms of the other techniques, the frequency monitoring and flexibility methods, I think they're pretty well limited to the low-frequency range and indicate overall structural response change.

DR. RUBIN: I would say flexibility monitoring was designed for a particular class of structure, the big shear-frame type of structure and what it's attempting to do is observe significant changes in the shear stiffness properties -- gross sheer stiffness properties.

DR. DAME: But it would not be perhaps applicable to indicating initiation of cracks?

DR. RUBIN: No, it would not. It requires essentially complete severance of the bracing.

DR. DAME: Essentially, changes in load paths. Acoustic emission is pretty much triangulation of ongoing crack propagation or initiation of cracks. Do you think that's fair to say?

Its use is dependant upon the end user. Is it important to understand that cracks are occuring in structures or initiating in structures; is that important?

MR. KNAPP: They are there, everybody knows it.

DR. DAME: What does it mean to you when someone comes up to you and says, "I can tell you when each and every crack will form in your structure." Do you care?

MR. KNAPP: One thing that's not been addressed here is how serious is a crack and where does it occur. We talk about critical joints on structures. One of the things the audience must remember is that piled offshore platforms -- I'm restricting it to that not semi-submersible floating structures, are entirely different animals; there are problems with them everybody knows about -- these are highly redundant three-dimensional space frame structures, and if you've ever gone out and tried to evaluate damage, you start getting a realization as to how much these can take and still stand there.

So that I don't know of a single critical joint on a well-designed modern platform today. In the early days before we knew much about tubular joints we had failures. You didn't have computer programs to analyze fatigue on a typical platform. You would probably have three or four joints with a fatigue life of 40 years as a design life. About 60 to 80 percent of the joints will have fatique lives greater than a thousand years, if that means anything.

You must remember that this design life states that 95 percent of the joints are better than this, so if you start looking at mean values of 50 you've got some joints with lives a couple of orders of magnitude higher.

So, where do you define your critical joint? Now if you have a crack down in the structure, you know it.

DR. DAME: How do you detect that now?

MR. KNAPP: Divers.

MR. GORDON: Isn't it conceivable that some of these techniques could save us a considerable amount of money if they indicated to you initiation of cracks, or that there is a severe crack?

MR. KNAPP: No, because right now nobody wants to admit there's a crack in the structure, either in government or in management, whether it's serious or not, and be pressured into repairing this. The other part of this business is that you've got to think about the problems of repair.

DR. DAME: So you want to quantify and qualify the cracks that are detected.

MR. KNAPP: That's right. All of these systems have uses. For instance, if you have a crack and find out about it, is it growing? Is it static?

Many of these things that pinpoint a location are very useful under the circumstances.

DR. DAME: An ongoing monitor.

MR. KNAPP: As far as what goes on in a structure? There's different degrees of agreement. The gentlemen from the oil industry may differ from me because I'm predominantly a structural design type, but with the structural redundancy that's present in an offshore platform it does not drastically concern me, because I'm going to have sufficient strength to resist whatever loads are applied in time to make a repair if it is needed.

MR. COLLINS: Essentially based on Norway -- when I said "hot spots", the people running the platforms have come up with their own analysis on this platform's stability. They pointed out you didn't need to monitor every joint; they did their own design and their own analysis, and they told you what joints they wanted you to do.I'm talking about the work we did. I did not go and tell them, "Hey, this is what we're going to do." They told me what they wanted, and ISS made a marketing survey for the platform owners and surveyed what inspection would be saleable to them.

MR. KNAPP: I am well aware of this. There are a lot of different arguments between people in the industry as to what is and isn't important.

If you talk to a metallurgist, he just can't stand cracks, and he wants to know if any of them occur. The bottom line in this business is, is it dangerous?

At least as far as I know there has never been a loss or a fatality due to the failure of a piled-steel template under any kind of loading. Some submersibles have gone down, jack-ups have failed. But I don't know of any failures on piled-steel templates.

VOICE: We had some wiped out in a hurricane.

MR. KNAPP: Yes, there have been platforms lost in the Gulf of Mexico. They were unmanned.

DR. DAME: They were abandoned old platforms?

MR. KNAPP: No, the oil patch evacuates in the event of a hurricane in the Gulf of Mexico. It's been going on for years, it's done on a routine basis.

We get good storm tracks. When the hurricane starts, you get all the extraneous people off and keep skeleton crews out there. You bring them in from the path, so we don't face the risk of the loss of life in the Gulf of Mexico. If you ever get anything in The Atlantic, that would be a different ballgame.

DR. DAME: But as we begin to go into colder areas, the environment in the Gulf of Mexico is relatively mild. Considering temperature and water depth that you'll be going into from now on, don't you consider the problem to be more severe?

MR. KNAPP: How about Cook Inlet? We've had platforms there since 1964.

MR. COLLINS: They're worried about those. We worked with those people; we worked quite a bit in Alaska. These platforms are starting to get old.

We worked with those people, they are concerned, and the North Sea people are concerned. Actually it's the platform owners that are concerned.

MR. KNAPP: We are concerned about the status of it. I would like to have an inspection method. I don't mean to deny this.

DR. COLLINS: They're worried. Some of them have been out there for a long time, and they're worried about the cracks that are developing in all these joints they don't know about, and they have enough of them where a big storm could cause the cataclysmic collapse of it.

DR. DAME: They're worried about fatiguing?

DR. COLLINS: Over a period of time. After the 10 years, they seem to start worrying about it.

MR. KNAPP: There's another special problem in Cook inlet, in that you have got high tide currents.

DR. COLLINS: You have also got all that silt. The divers have zero visability.

MR. SMITH: I think we are looking at a whole series of techniques, to cover different types of situations. One is the very sudden event, such as a storm, where damage can occur, and you need to know something right away. The other ones are some of the long-term situations, where you have old platforms, where you don't have any requirements for periodic inspections right now. So we are just developing these techniques as a helpful guide.

DR. DAME: This is probably a general question. Do you think that the State-of-the-Art technology in these NDE methods is currently appropriate or sufficient to commercialize the systems, or do you think it's more appropriate that more laboratory work be done? Can we sell these systems? Can we use them? Or do we have to validate them more by laboratory tests?

MR. KNAPP: I want to make one comment on that, because I have heard some very good work presented here, and I think all these have use, but be very careful about how you sell it, because when frequency monitoring first came out, Stan Campbell went around and got a bunch of oil companies together; I think Shell furnished a platform, and it fell flat on its face.

Now, the hardest thing to do is to salvage the good points of a system which failed. So what I am saying is, all these methods have application someplace. Be careful how you push it.

MR. BOLELHO: I particularly feel that more field trials should be tried.

DR. DAME: A simulated damage scenario?

MR. BOLELHO: I feel more work should be done. Perhaps a few methods are almost on the verge of being possible to be sold, but I still think more work should be done.

DR. DAME: Isn't it very difficult, though, to evaluate some of the techniques in a field situation, such as supplying sufficient loads so you can see a joint failure, or cracking? Isn't that where laboratory testing has more application?

MR. BOLELHO: I am not so sure about that, because special joints could be designed to fail under relatively mild conditions.

DR. DAME: So you take an old platform, remove a joint?

MR. BOLELHO: Instrument it, and perhaps change a joint or joints. Make it collapsible, let's say, under mild conditions.

VOICE: When you field test it, you get into a lot of practical problems, not just testing the technique itself, but are you able to deploy all this equipment? Can you get the men down there? Can they hang on while they try to hold the instruments on the joint? There are a lot of things you find out about it. It may be a technique theoretically that will work fine in the laboratory, but in a practical sense, when it gets out in the field, they just can't do it.

DR. DAME: That's important to find out, though, isn't it?

VOICE: That's why you have to have the field tests.

DR. DAME: But also, isn't it much more expensive? You're going to an order of magnitude more expensive test when you go into a field test than you are in a laboratory.

MR. ALEA: I don't know about that, because when you go into the field you have very specific objectives. When you go into a labortory, all of a sudden your objectives become very broad. Sometimes the laboratory tests may turn out to be more expensive.

DR. DAME: That may be true. But in a particular region of the ocean where you have diving expenses and submersible expenses --

MR. BOLELHO: On the other hand you could have several companies join the project. It wouldn't be one organization; it would probably be a joint industry project. The industry would profit from that, as a whole.

DR. DAME: Would management today, under tight budgetary restrictions, be willing to fund an experiment?

MR. BOLELHO: I can't speak for all companies, but in particular, Chevron would consider that. No doubt, it will depend on the problem involved, and the benefit the company would get. But it would be, certainly, considered, even at this time of tight money.

MR. KNAPP: Mine would not. Amoco is under very tight budget constraints for any type function. The best thing is to come back in a couple of years. I'm serious. When the profit flow and the cash flow turns up. The oil industry as a group is under very tight budgetary restraints.

You might float it, I don't know, but I'd say your odds of getting it by through this year or the next fiscal year are pretty low.

VOICE: I think the bottom line of doing a field test may be more expensive, but I don't think you are going to be able to sell it to the industry until you do the field test.

DR. DAME: Until you validated them successfully in the field.

VOICE: Right. I think you are going to have to show the strong point or discover what the weak points are, out in the field, before anyone from the oil companies would touch it.

DR. DAME: When would they be satisfied? After one set? Or how many do you have to go through?

VOICE: That's hard for me to say.

DR. DAME: That could be very difficult.

MR. MASTENBERRY: My name is John Mastenberry from NDE Technology. We developed a leak detection system for offshore pipelines and we went through a test where we left it offshore for three months, did acoustic monitoring for deformations. We went out there after three months, and brought it back to shore, but still, when you try to sell it, you still have a problem because they said, "Who has bought the system." I think that's a big problem.

DR. DAME: You mean your track record?

MR. MASTENBERRY: You are going to actually have to give something to somebody to keep. But if you just use a prototype out there on the rig, and install it and set it up, they're still going to say: Did you check this? Did you check that? You need a track record, I think.

DR. DAME: What about a research and development effort by the potential user, who would share in the developments and possibly the profits in the future?

MR. MASTENBERRY: That's a good idea. We did it with Shell. We are thinking about doing a commercial version of it, too, to sell to other customers. If you want to make a profit, you want to make it useful worldwide.

DR. DAME: If an oil company is in a profit posture, and has sufficient revenues for R&D, I guess that's one factor to bear in mind.

MR. MASTENBERRY: Still, the point is, has someone used it long term? Not like a two-week test offshore. It has to be a long term.

DR. DAME: I think from what some people said, even then you would have skeptics.

MR. COLLINS: That's right.

MR. MASTENBERRY: But if you had a system in -- let's say you had a prototype, with whatever one of the systems, you would still have to have a commercialized version used for a long time, that someone can look at over a period of a year or so, or two years, and I think that would sell.

DR. DAME: Are these techniques going to add expense to inspection, or are they going to save money?

MR. MASTENBERRY: Cost-effectiveness is the most important thing.

DR. DAME: But are we going to have to now continue with diving inspections and random dec or acoustic emissions?

MR. MASTENBERRY: You will never get away from diver inspections, no matter what. That's the confidence factor.

DR. COLLINS: We have been around a lot of the oil companies trying the same situation of having a group of them fund the program. But like the people from the oil companies say, they're under great pressure now. Even though Oceaneering was very successful the last couple of years, I would just venture that this cost of implementing a field system in the ocean is a tremendous cost, and I don't see the oil companies are going to do it. I would bet right now a 99-to-1 probability that they won't do it. Maybe people from the oil fields don't want to say anything, but I don't think they are going to do it, and if I were them, I would wait around till the government did it. It saves them the money, and they can observe things, and what they like, they can do; what they don't, they won't have to do.

That's a business decision. If I was in their position, I would do the same thing.

DR. DAME: Unfortunately, we're not in the same type of Administration we have always been in, in the past. Now, more is pushed onto the private sector.

DR. COLLINS: We can look to the future. The future will tell us if they will do it, but I would like to ask the oil people how much have their companies put in this type of research in the last five years? If they gave us those numbers, in terms of 200K, a million dollars, or whatever, I would be interested.

Most of the companies that I know of this type have not put in that much money. I don't blame them. Maybe I am wrong, but I don't believe the American companies have.

VOICE: I know that some oil companies have research staffs working on some methods on their own. The fact that they haven't deployed these methods themselves is probably some indication that they are not ready for it.

DR. DAME: I think as far as Random Dec is concerned, Exxon has purchased a system for a refinery, and I know they are doing continuing research in the area themselves.

MR. MASTENBERRY: There is one comment I would like to make, on the practical aspects, in the sense of staying on the structure for 10 years or five years.

DR. DAME: You mean the on-board, continuous monitoring?

MR. MASTENBERRY: Right. What are the odds on that being performed? If one doesn't work after two years.

MR. BOLELHO: You're talking an even longer life than that.

MR. MASTENBERRY: Well, 10 years.

MR. BOLELHO: You ought to be talking 13 years. I am not saying that's the design life.

MR. MASTENBERRY: I am talking about an instrumentation package, 10 years.

MR. BOLELHO: It should be used the whole life of the platform. And apparently, the people in Norway were saying that, when the platform is reaching the end of the design life, that's the most worrisome part.

DR. COLLINS: Maybe it can go further than they predicted. It could be for extending the life, too.

MR. BOLELHO: Ideally, that is what you would like to have. It may be impossible to achieve.

MR. MASTENBERRY: What I was getting at is that 10 years is a very good instrumentation package. But in 10 years, the State-of-the-Art changes so much.

DR. DAME: What is the prognosis for continued research and support of research from the government side?

MR. SMITH: Well, we are not dead. I guess we are going through the same hard times as the industry is, on availability of funds for research. We do have some funds. Each project is being closely scrutinized for the way it can apply to our operations and our needs, as well as to what area the industry should be working in, and what area we feel we could make our contribution in.

We would not be adverse to receiving information or proposals on certain projects. We have an ongoing research program. We hope it continues. We will probably be continuing to a lesser extent with Random Dec.

If we felt it would meet our needs, we might consider other systems. We would be interested in working with industry. We are involved in quite a few industry projects in other areas, ice mechanics, what have you, and there was a chance to have a joint industry program to actually, maybe, cause damage to a structure and see the effects.

DR. DAME: That's encouraging.

MR. KNAPP: I want to make one further comment on this. To sort of set the stage, we talk about platform life. In the initial stages, when your engineers estimate how long these are, they're probably the world's worst pessimists. With secondary and tertiary recovery, what we're finding are that these are extended far past what the original design life is.

In the offshore regions, we are just starting to get into this. So I would say that in the not-too-distant future, methods of inspection will become far more important than they are right now. This is one of the things that's caused us a lot of problems. You put a platform out there. It's just come out of the yard, and suddenly everybody has to inspect it. It's got a design life of 20 years, and you don't really expect to find anything down there, and we don't. Yet we spend a lot of money inspecting it. This causes companies to resist these sort of techniques.

Facing up to the realities of it, as these platforms get older, and they're wanting to extend the life of these fields, now, we are going to have to start expecting some damage, and possibly some limitation on underwater works. That's where I think these inspection techniques will play a very important part.

MISCELLANEOUS MATERIAL

January 3, 1983

Box 666, Pacific Palisades
Calif. 90272 (213) 454-0777

MEMORANDUM

Subject: Structural Monitoring System
Employing Electro-Optic Technology,
Effort to Date and Current Status

1. The E-O system was initially conceived as a technically attractive and economic alternative to a conventional discrete strain-guage NDE system for the Alaska Natural Gas Transmission System. This system involves the monitoring of heave and subsidence of many miles of large-diameter pipe buried in permafrost. The concept was evaluated by the support contractor to the Office of Federal Inspector for the ANGTS and given top priority for development. The subsequent deferral of the ANGTS project has similarly delayed funded E-O system development support.

2. Laboratory tests have been performed which verified the E-O phenomenon and its measureability on a qualitative basis.

3. A patent application has been filed. A brief description of the method follows:

> Based on the changes in path length and refractive index of a structure-attached fiber-optic cable when bending or deflection occurs in the structure, changes in interference, intensity or reflection of a light signal in the optical fiber can be utilized to measure the structural deflection. This measurement applies to the magnitude, direction, frequency and location of the deflection. Multiple series measurements are inherently possible over long structures from a remote point on a passive basis with a continuous sensor/cable/transmission system.
>
> The method is generally applicable to linear structures (civil, vehicular and industrial) and to earth movement monitoring on a time-domain basis.

4. The physics of the E-O phenomenon have been mathematically analyzed for technical feasibility and sensitivity. A general system design has been configured, and a preliminary investigation has been undertaken relative to fiber optic cable development, attachment and testing.

Depending upon the anticipated deflection characteristics of a particular structure, the magnitudes and frequency involved, the sensitivity of measurement desired and overall path length, individual system designs can be formulated within the limits of system gain and measurement threshold. For pipeline application, for example, several kilometers of pipeline should be monitorable by the E-O system from one end of the pipeline.

5. A development program has been undertaken including:

Mathematical modeling, verification and analysis;

Laboratory testing and development of the system;

Prototype system design, fabrication and field installation for a specific application;

Field operation and data acquisition.

The total program has been costed at about $500,000 and is partially funded from private sources.

6. Presentations on the technical features of the system and the schedule of the development program have been made to selected major integrated petroleum firms. Specific positive interest has been received for application of the E-O system to marine risers, tension-leg platforms and arctic pipelines. Discussions are continuing, involving submittal of test data and phased development.

7. Similar vue-graph supported presentations can be arranged to qualified industry groups, particularly in the civil-structure field (bridges, buildings, dams and tunnels) and vehicle-structure field (space craft, aircraft wings and helicopter blades), for participation in the development program on a fundable basis. Inquiries should be directed to the undersigned at the foregoing address.

8. The development work is centered at QUESTRON Corporation, La Jolla, California.

R. W. Griffiths

RWG/JD